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SPACE THE FINAL FRONTIERS

The missions that will unravel the mysteries of the Universe

Voyage to Venus, our fiery neighbour

A new race to the Moon has begun

The rover that will search for life on the Red Planet

The hunt for the oldest galaxies in the Universe

What will New Horizons discover beyond Pluto?

Secrets of the supermassive black hole Why scientists want to harvest space rocks

The next generation of exoplanet hunters

> Planet 9: how we'll find it

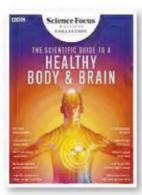
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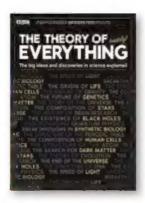
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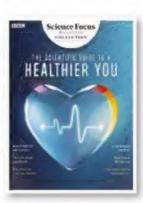




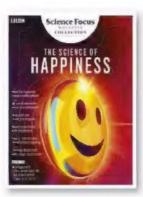
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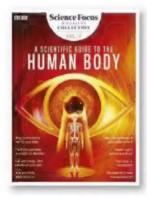
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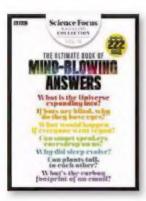
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Editor Daniel Bennett
Managing editor Alice Lipscombe-Southwell
Production assistant Holly Spanner
Commissioning editor Jason Goodyer
Staff writer James Lloyd
Editorial assistant Amy Barrett

ART & PICTURES

Art editor Joe Eden
Deputy art editor Steve Boswell
Designer Jenny Price
Picture editor James Cutmore

ADVERTISING & MARKETING

Group advertising manager Tom Drew Advertisement manager Sam Jones 0117 300 8145 sam Jones@immediate co.uk

LICENSING & SYNDICATION

Director of licensing & syndication Tim Hudson International partners manager Anna Brown

PRODUCTION

Production director Sarah Powell Production co-ordinator Emily Mounter Reprographics Tony Hunt, Chris Sutch

PUBLISHING

Commercial director Jernima Dixon Content director Dave Musgrove Managing director Andy Healy Group managing director Andy Marshall CEO Tom Bureau

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Chair, editorial review boards Nicholas Brett
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Welcome



When we first landed on the Moon in 1969, humankind collectively marvelled at the ingenuity of our species. We had explored the surface of our own planet and had now successfully set foot on another world as well — no problem was insurmountable for us. While we'd landed uncrewed craft on the Moon before that, and had already sent probes

to Venus and Mars, it was arguably the Moon landing that energised us to continue exploring the cosmos, so we could unlock the secrets of the Universe and perhaps even life itself.

We set our sights further afield than the Moon, with missions to Mars, Jupiter, Saturn and beyond. But we also started building space stations that would allow us to explore the effects of space while remaining in comfortable proximity to our own planet.

Despite our efforts, however, many aspects of the cosmos remain a mystery. For example, despite all the missions to the Moon, we still know very little about its far side. That could soon change because China's Chang'e 4's craft successfully touched down in 2019 (p10). In January this year, they released their first set of data, which is now available for astronomers to pore over – in the process, they'll revolutionise our knowledge of our Moon. Mars has been the destination of choice in recent years, but we're still not sure if it hosts life, so later this year ESA will send a mission to the Red Planet to find out if it does (p26). And our other planetary neighbour, Venus, has been somewhat forgotten over the last few decades – that's why teams of scientists think it's high time we went back (p18).

Speaking of planets, we're still not sure if our Solar System hosts a huge ninth planet beyond Neptune, so we meet the scientists who are hunting for it (p60). Farther afield, in solar systems beyond our own, scientists are certain there could be Earth-like worlds. By using ingenious methods and a new breed of telescopes, they're sure they can spot them (p74).

Enjoy!

PINTEREST -

Alice

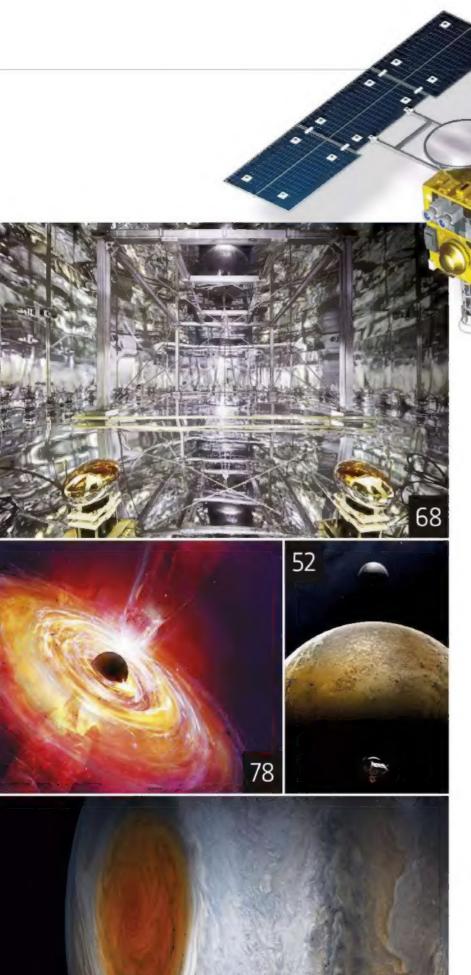
Alice Lipscombe-Southwell, Editor

Chang'e 4's lunar rover trundles across the surface of the Moon while the lander looks on



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Sol mates

FLORIDA, USA

In the early hours of 6 February, Solar Orbiter will set off from Cape Canaveral in Florida to begin its journey to the Sun. This joint NASA and ESA mission will unravel some of the mysteries of the Sun, taking high-resolution photos of its polar regions for the very first time.

Data gathered by the probe will help us understand how our star creates and controls the heliosphere – a giant bubble of plasma that surrounds our Solar System – as well as investigating coronal mass ejections and solar winds.

During the mission, this spacecraft will be exposed to sunlight 13 times more powerful than we feel on Earth. To protect the inside of the probe from the intense heat and radiation, Solar Orbiter's instruments are hidden behind small 'peepholes' in the heat shield, which will close when not in use.

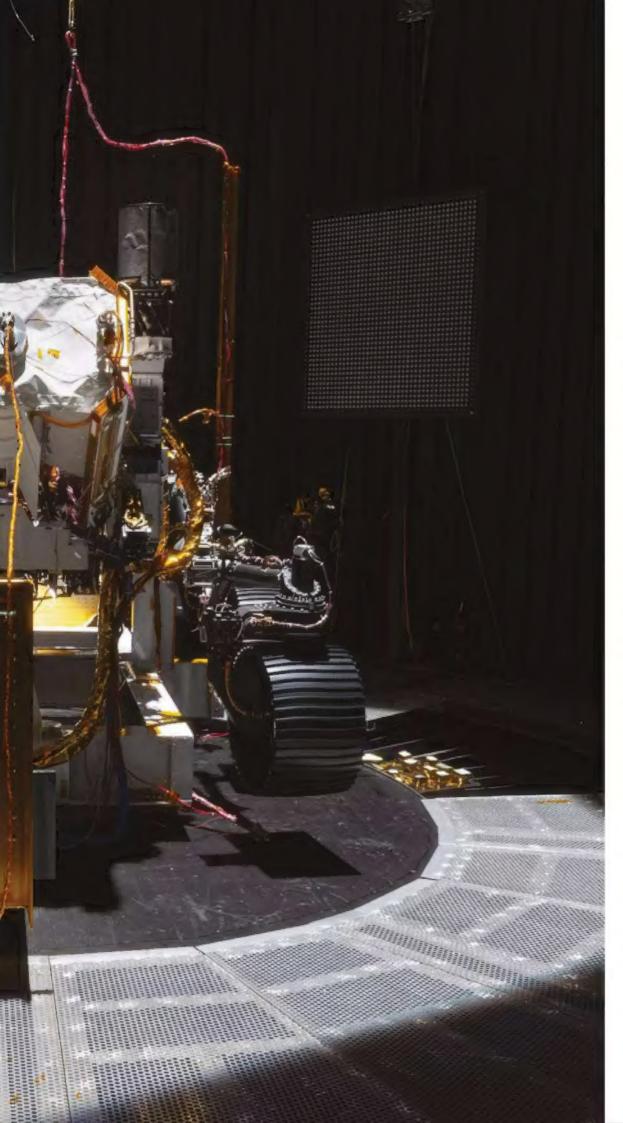
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A light touch

CALIFORNIA, USA

An engineer uses a solar intensity probe to carefully measure the amount of artificial sunlight reaching different parts of NASA's Mars 2020 rover, at the Jet Propulsion Laboratory in California. Using this crucial data, scientists will be able to determine how this car-sized robotic scientist will interact with the Sun while on the Martian surface.

For the test, powerful xenon lamps were used to simulate the Sun, as the spectral output of xenon is similar to that of our star. The lamps were illuminated several floors below the craft, then bounced off a mirror at the top of the chamber onto the rover.

Based on the design of Curiosity, which landed on Mars more than seven years ago, this as-yet-unnamed mission will carry new instruments including a core drill and helicopter drone.

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INSIDE CHINA'S PLANS TO BUILD A LUNAR BASE

A COLIN STUART



arly January was the one-year anniversary of the first mission to land on the far side of the Moon — China's Chang'e 4. To mark the occasion, the Chinese space agency released the data and images they'd gathered so far.

Looking back to 3 January 2019, there was much excitement when China successfully lowered their Chang'e 4 mission onto the Moon's surface, and just 12 hours later, the Yutu 2 rover trundled down a ramp to imprint its tyre tracks in the lunar dust on the Moon's far side for the first time. "It's a hugely significant moment in the history of space exploration," says Prof Ian Crawford, a planetary scientist at Birkbeck University of London.

Chang'e is named after the Chinese goddess of the Moon, with Yutu being her pet white rabbit that is believed to be visible on the lunar surface, much like the man in the Moon here in the West. Chang'e 4 marked a return to the Moon's surface after years of human indifference, as we've strived to explore the rest of the Solar System.

Interest in all things lunar began to wane after the Apollo missions ended in 1972, with even robotic missions to the Moon's surface fizzling out by 1976. And so it remained until December 2013, when China landed the first Yutu rover on the near side of the Moon as part of the Chang'e 3 mission, making them only the third nation after the US and Russia to successfully dispatch and land a lunar rover.

But the Chang'e 3 mission wasn't without its difficulties, as a technical fault hampered the rover's movement not long after landing. The suspected culprit was more frequent encounters with rocks than originally envisioned. Considering these issues, the Chinese space agency's subsequent move was a brave one. "It's quite impressive that their next attempt was on the far side of the Moon," says Crawford.

Due to the Earth's gravitational pull, we only ever see one side of the Moon – the other is permanently turned away from us. That's why Chang'e 4 landed during a new Moon, a time when our side is dark and the far side is completely illuminated by the Sun. Regardless of which side they land on, missions to the Moon have to endure two weeks of cold darkness, followed by a fortnight of intensely bright daylight.

◆ The only way to learn more about the far side is to send probes (or people) around the back for a closer look. While the first image of the far side was taken in 1959, it has taken until now to land a probe on it. NASA rejected the idea of sending Apollo 17, the last human landing mission, there in the 1970s, partly due to the difficulties with communication − the Moon itself blocks direct radio signals with Earth.

LUNAR LANDING

To get around the communications problems, the Chinese parked the Queqiao (Magpie Bridge) satellite in lunar orbit in 2018 to relay messages back home. Queqiao orbits 65,000 kilometres beyond the Moon and transmits signals back to China and other base stations around the world. This system makes the mission more of an intricate ballet than near side landings. Mission scientists spent four weeks prior to touchdown testing out this crucial relay system. The far side is also far more jagged compared to the relative smoothness of the near side, meaning there are even more potential hazards to avoid on landing. According to Prof Bernard Foing, executive director of the International Lunar Exploration Working Group, success required "a number of critical manoeuvres including launch, trans-lunar injection, lunar capture, de-orbiting, stabilisation and controlled descent, hazard avoidance, soft landing, the deployment and commissioning of rover and instruments." It all seems to have worked perfectly. "The whole process was as expected, the result was pretty precise and the landing was very stable," chief designer Sun Zezhou told Chinese state media shortly after confirmation of success reached home.

Their chosen landing spot was the 180km-wide Von Kármán crater, named after aerospace engineer Theodore von Kármán who made many key advances in the field of aerodynamics in the 20th Century. It's an impact site superimposed on a much bigger collision scar known as the South Pole-Aitken basin. "It is the Moon's largest, deepest, and oldest impact structure," says Foing. Place Mount Everest on the crater floor and its peak wouldn't be close to poking out over the top. It's of extreme geological interest as it could provide clues about



ABOVE

Technicians at Beijing's Aerospace Control Center celebrate Chang'e 4's successful landing on the Moon

ABOVE RIGHT

Selfie time! The Yutu 2 rover trundles across the Moon's surface, making fresh tracks as it goes the way the Moon formed from debris thrown into space after a small planet collided with the infant Earth. The crater was flooded with lava during the Moon's early days, meaning the crater floor is incredibly smooth and far less dangerous to land on than elsewhere on the far side. "It was very much chosen with safety in mind," says Crawford.

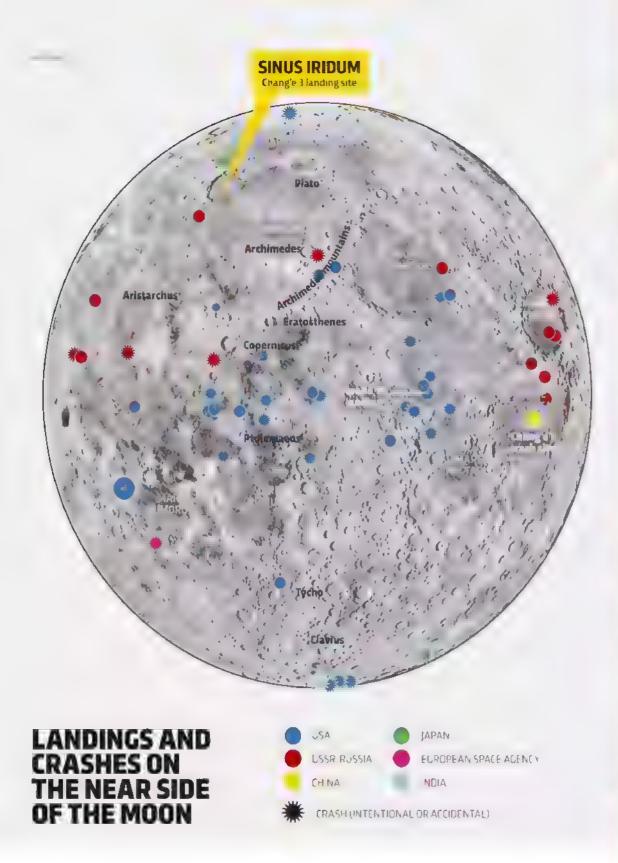
The colossal impact that formed the Aitken basin could well have penetrated deep into the Moon's mantle, exposing deeper basalt material onto the surface. "No one has ever measured the composition of far side basalt before," says Crawford. Doing so isn't a certainty, however, as the interesting stuff might have been covered over by the lava flows that flooded the basin. Like any space mission, Chang'e 4 scientists had to balance risk and reward. So they included another way to get data on the Moon's subsurface — the Yutu 2 rover carries an instrument called Lunar Penetrating Radar (LPR) that can scan the structure of the lunar far side down to a depth of 100 metres.

Geology is far from Chang'e 4's only aim. A wide array of other experimental instruments were also crammed onto the back of Chang'e •

"WHILE THE FIRST IMAGE
OF THE FAR SIDE WAS
TAKEN IN 1959, IT HAS
TAKEN UNTIL NOW TO LAND
A PROBE ON IT"



WHY DO WE ONLY EVER SEE ONE SIDE OF THE MOON? Thanks largely to Pink orbit us (both 27.3 days). So: i-Floyd's 1973 album, the Moon is rotating, we just astronomers regularly never see the other side. The contend with talk of the 'dark Moon is always half lit up side of the Moon'. There isn't and half not (day and night, ⊵one. At least there's nojust like on Earth). Where this epermanently dark side of the sunlight falls depends on the · Moon. It is true that we only Moon's position around the rever see the front of the-Earth. When between us and r Moon and not the back due the Sun, the back isto an effect called tidal completely illuminated -Flocking. Over time the Earth's definitely not dark. The only gravity slowed the Moon's time it is completely dark is: rotation on its axis until it when we are experiencing \mathbf{a}_{S} matched the time it takes to full Moon.



• 4 and carried to the Moon. The far side of the Moon is considered by many astronomers to be an ideal place to build a radio telescope. Sheltered from the background hum of the Earth by the Moon itself, any observatory there would be free to make sensitive measurements of faint astronomical radio signals. Chang'e 4 includes an instrument capable of listening to space across a wide range of frequencies. Should its results prove fruitful. Crawford believes it could usher in much more sophisticated radio astronomy missions in future. However, the majority of Chang'e 4's non-

geological experiments are designed to scope out the possibility of future human missions back to the Moon. According to Foing, one experiment called ASAN "will study how the solar wind interacts with the lunar surface and perhaps even the process behind the formation of lunar water." The South Pole-Aitken basin is thought to be home to large quantities of water ice — a crucial resource for tomorrow's Moon dwellers. Would-be astronauts will also be unprotected from the harshness of space. They'd be prone to sizeable doses of radiation from solar storms and cosmic •

MINING ON THE MOON

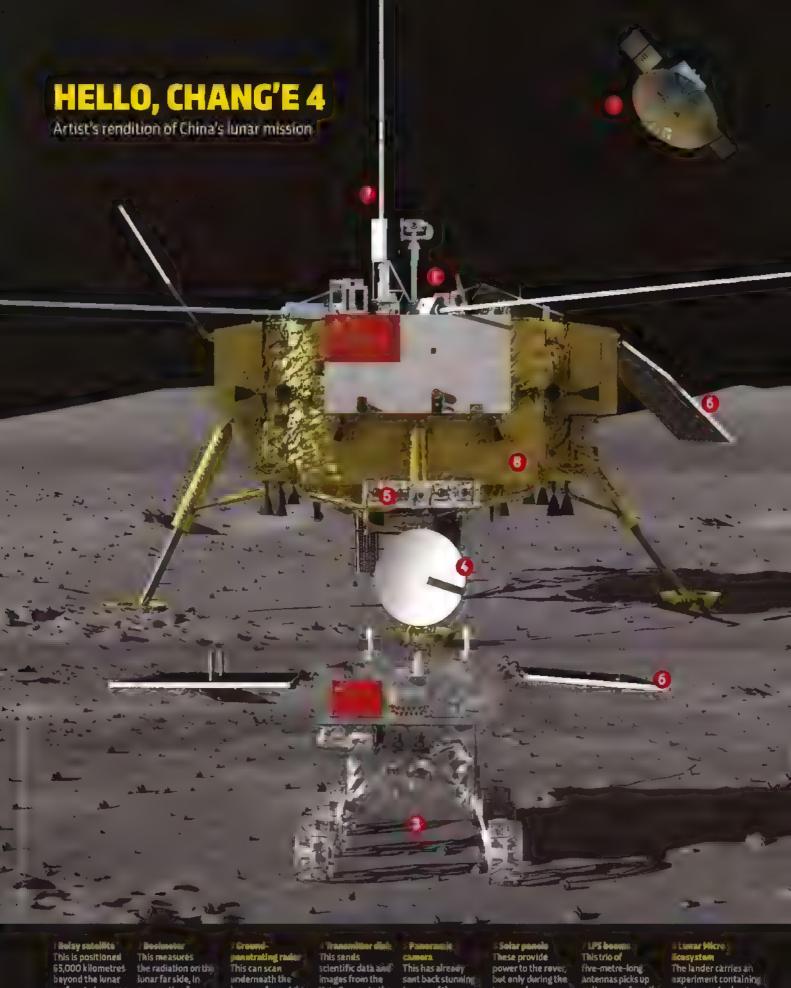
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beyond the lunar surface to bounce to Earth.

This measures the radiation on the lunar far side, in preparation for future human missions to the Moon

lunar surface, right down to a depth of 100 metres.

images from the Yutu 2 rover to the colay satellites

sent back stunning images of the landscape on the fair tide of the Moon

but only during the two weeks every month when the far-side is illuminated.

antennas picks up radio waves from the early Universe, just after the Big Bang

experiment containing various seeds along with silkworm eggs, but it was called off after a few days





• rays generated by stars exploding elsewhere in the Galaxy. The Lunar Lander Neutrons and Dosimetry (LND) experiment, developed in collaboration with Kiel University in Germany, assesses the strength of that dose in the vicinity of Chang'e 4's landing site.

LIFE ON THE MOON?

The experiment that fired our collective imaginations was the Lunar Micro Ecosystem. This small, sealed container housed various seeds, along with silkworm and fruit fly eggs. After landing, the experiment was powered up and the temperature adjusted to 24°C. A tiny camera kept watch to see if living things could eke out an existence in the harsh, alien environment. On 15 January 2019, it was reported that some of the seeds had sprouted, and images of the cottonseed seedlings were released. But the success was short-lived, when it was reported that the shoots had failed to survive the lunar night. None of the other organisms showed any signs of life and the experiment was called off a few days into its planned 100-day stint. Still, decades from now, humans could look back at this experiment as the beginning of life on the Moon. Make no mistake that is what China is gearing up for. Their recent launches are following roughly the same pattern as NASA before the Apollo era. First, launch satellites to the Moon (Chang'e 1 and 2), then land a rover on the near side (Chang'e 3). This far side landing is a real show of intent. "The Chang'e 4 mission will advance [their] technical maturity for future robotic and human landings," says Foing.

China wants to be considered in the same

"DECADES FROM NOW, HUMANS COULD LOOK BACK AT THIS EXPERIMENT AS THE BEGINNING OF LIFE ON THE MOON"

league as the US and Russia when it comes to space exploration. Yang Liwei became the first Chinese astronaut (also called a taikonaut) in 2003. So far, 12 taikonauts have been into space, some of whom were sent to a prototype Chinese space station called Tiangong-1, which remained functioning around Earth from 2011 to 2018 before falling from orbit over the southern Pacific Ocean and reportedly burning up in the atmosphere. Now, the Chinese have begun the construction of a new, more ambitious orbital outpost in a bid to match the stature of the long-established International Space Station. They hope to have it finished by 2022. What they learn there, combined with the lessons from Chang'e 4, could see China send the first taikonauts to the Moon as early as 2025. In the meantime, more robotic missions are already in the pipeline. "Their next steps will be Chang'e 5 and 6," says Foing. The former is scheduled to launch this year and will aim to return samples of lunar material from the near side.

ABOVE LEFT

Yang Liwei, the first Chinese astronaut (also called a taikonaut), waves to the crowds after stepping out of the Shenzhou-S re-entry capsule in October 2003

ABOVE

Tiangong-1, China's first space station, orbited the Earth between 2011 and 2018



Success will demonstrate that the Chinese can return material from the Moon, paving the way to bring humans back too. "A number of other robotic landers are planned that could build up a de facto lunar robotic village," says Foing.

SPACE RACE

There is another potential advantage to be gained from the recent Chang'e missions. No other country has landed anything on the Moon since the 1970s. Having readily available technology to do so could place China in the lead to exploit the Moon's natural resources. By analysing the composition of the lunar far side, they could gain valuable information about the kind of treasures potentially on offer. The Moon is already thought to contain significant amounts of helium-3, which is a chemical that's exceedingly rare on Earth. What else could they find squirrelled away in these unexplored rocks? Could a modern space race be triggered as superpowers compete once again for off-Earth supremacy? Some quarters are nervous about what it could mean for the potential Chinese militarisation of space. The country is party to the 1967 Outer Space Treaty, which forbids signatories from placing weapons of mass destruction on the Moon. However, China has previously flexed its space muscles, most notably when it destroyed one of its own weather satellites in 2007 using a missile fired from the ground. While other space agencies have been quick to congratulate the Chinese on their latest success, and talk openly about potential joint projects, it remains to be seen whether the future will be more about competition or cooperation. SF

ADVOET VALUE

The success of China's Chang'e 4
landing has again brought the
country's space programme into
the spotlight, and raised the
question whether China is now a
serious player in space
exploration. The answer is
unequivocally 'yes'. While it is
easy to rebuff these latest
accomplishments by pointing out
that the United States and Russia
landed spacecraft on the Moon
more than half a century ago, this

misses the point. Though they did not generate as many column inches as Chang'e 4. there were 39 Chinese rocket launches in 2018, only one of which failed. In comparison, Russia launched 20 rockets, with one failure; and the United States launched 34, all successful. Europe lagged behind with eight 1 launches with one failure, while Japan and India Jaunched six and seven rockets respectively. It looks likely that China's position: will become increasingly difficult: to ignore, particularly as the country is open for collaboration - Chang'e 4 carries experiments from Swedish, German, Dutch and Saudi Arabian researchers. In 2017, 3 the Chinese announced plans for a permanently crewed space station as part of their Tiangong or Heavenly Palace programme. Notably, the country signed and agreement with the United Nations to allow experiments and astronauts from other countries. to use the station. The core module of the space station is planned to be launched in 2020 with proposals for collaborations coming from 27 countries. It's.

unlikely, however, that the US will be involved as Congress banned --NASA from using its funds to host: Chinese visitors in 2011. This division between the superpowers leads to the question of rivalry and whether China's -interest in the Moon will spark a new space race. It's complicated.imesThe same team of space agencies responsible for the International Space Station (NASA, ESA, Russia's Roscosmos, Japan's JAXA, and: Canada's CSA) are already developing the Lunar Orbital Platform-Gateway (LOP-G), LOP-G is a space station that would carry// a four-person crew in an orbit around the Moon, sometime after the mid-2020s. But there are: those who say it is a costly distraction from sending astronauts to Mars. So if anything, \parallel the Chinese interest in the Moon could lead these critics to call for: efforts to be concentrated on Mars, in order to reassert NASA's lead in space. Such a plan, however, would inevitably bring NASA into disagreement with Its,, international partners, all of stwhom are known to favour going: to the Moon.~

So the future is going to be interesting. Unlike the space race of the 1960s, when the United States and Russia went head-to-head to land on the Moon, we are likely to see two parallel space programmes develop, one led by NASA and the other by the Chinese. And although we are unlikely to see direct rivalry in their goals, you can be sure that both sides will be keeping an eye on each other.

COLIN STEART

Colin is an astronomy writer. His linest book, How To Live In Space (E16.99, Andre Deutsch), is out new





Scientists want to return to Venus, so they can try to find out why it morphed from a pleasant planet into a fiery and inhospitable hell hole

N ABIGAIL BEALL

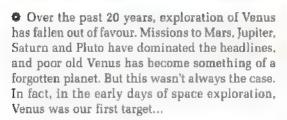
e have a toxic twin. Venus is the closest planet to Earth, both in size and often in distance, yet the surface conditions couldn't be more different. One planet is home to abundant life, the other is hellishly

hot, choked by an atmosphere of carbon dioxide that creates a surface pressure equivalent to being almost one kilometre underwater on Earth However, things weren't always this way. Once upon a time, Venus might have had a similar climate to Earth, complete with water of eans and plate lectonics.

Finding out what went wrong with Venus is the question behind a fresh surge in missions to explore the planet. It's an endeavour that promises to shed new light on how planets become habitable, and could even guide our search for life elsewhere in the cosmos.







EARLY EXPLORERS

In 1962, NASA's Mariner 2 spacecraft flew past Venus, becoming the first space probe to encounter another planet. Five years later, the Soviet Venera 4 probe entered the Venusian atmosphere, becoming the first to enter the atmosphere of another world. The same year, NASA's Mariner 5 set off on the space agency's second successful flyby mission. The exploration of Venus was in full swing.

What followed was a series of missions, some failures but mostly successes, to find out more about this planet that, at first glance, appeared so similar to our own. But from the 1980s onwards, the pace slowed down considerably. NASA's last dedicated mission to Venus was the Magellan spacecraft, which launched in 1989. The reason for this drop-off? As the data started to come back from our twin planet, astronomers interpreted the high



"FOUR AND A HALF BILLION YEARS AGO, THINGS LOOKED DIFFERENT. YOU'D SEE WATER AND A PLEASANT CLIMATE ON MARS, EARTH AND VENUS"

ABOVELEFT

Earth and Venus are extremely similar in size. giving them the moniker of the 'twin planets'

ABOVE

NASA's Mariner 2 flew past Venus in 1962 and was the first space probe to encounter another planet

temperatures, suffocating atmosphere and impact craters they saw on the surface as evidence that Venus was biologically and geologically dead—and therefore of limited interest to scientists searching for extraterrestrial life or Earth-like geology. The pristine condition of most of Venus's impact craters, for instance, indicated a comparatively young surface, which suggested that some kind of global, volcanic event in the planet's history had completely resurfaced the planet, resulting in a dramatic reduction in geological activity.

This idea, however, is still up for debate. "Since then, a lot of people have done [computer] modelling that indicates that this is a very unlikely interpretation," says Dr Sue Smrekar, a planetary geophysicist at NASA's Jet Propulsion Lab, and self-confessed 'Venusophile'. Instead of one huge event, says Smrekar, "you could have 'steady state' [smaller and reoccurring] processes of volcanism to produce the impact crater record." Settling this

debate, and discovering the true story of Venus's history, is the motivation behind a proposed NASA mission that's being led by Smrekar, called VERITAS.

SAME PLANET, DIFFERENT CLIMATE

Today, the average surface temperature on Venus is 462°C. But the planet wasn't always such a hot mess. When the Solar System was in its early stages, four and a half billion years ago, things looked different. "You'd see water and a pleasant climate on Mars, Earth, and Venus, most likely," says Dr Richard Ghail at Royal Holloway, University of London, who is lead scientist of a proposed European Space Agency (ESA) mission to Venus, called EnVision.

Two billion years later, it was a different story. Mars was basically dead and Earth was a frozen snowball, says Ghail. Earth was active as a planet, in the geological sense, but frozen solid, resembling how Jupiter's moon Europa looks today.

"Venus probably looked like a hot version of the Earth," says Ghail. "It still had oceans but they

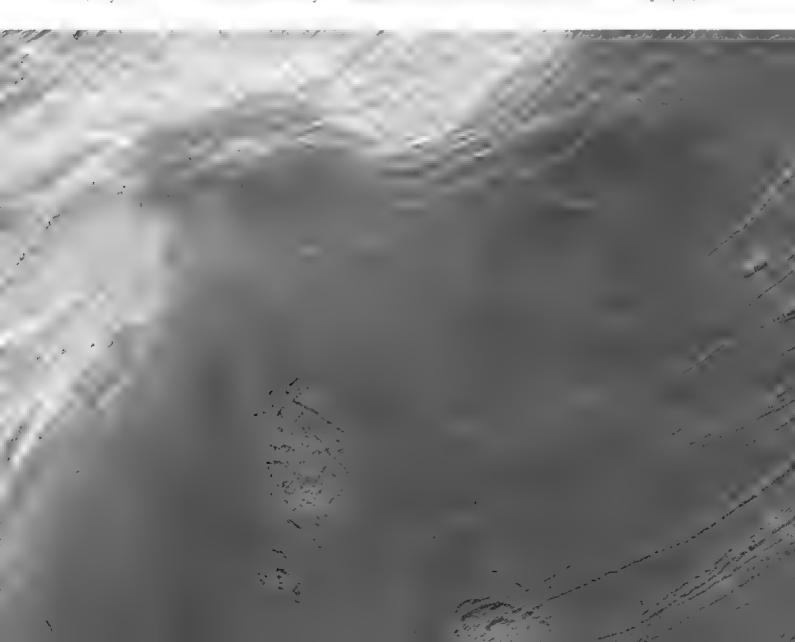
were evaporating... it was starting to get really unpleasant." At this point, "you'd think all three of these planets were doomed biologically. And yet, Earth came out of that and into this new phase where life appeared," he adds.

Understanding Venus's geological history will be crucial to piecing together the contrasting fortunes of the two planets. While Venus is not known to be geologically active today, its past patterns of volcanic activity will be a vital clue in helping us find out more about the planet. The amount of volcanism could be linked to the amount of toxic sulphur dioxide in Venus's atmosphere, for example, which is a key reason why it is uninhabitable. "Ultimately, we want to understand why Venus and Earth are different," says Smrekar.

The surface of Venus has not been mapped since NASA's 1989 Magellan mission. "We now have better topography maps for Pluto than we do for Venus, so it's time for an update," says Smrekar.

This is where VERITAS (Venus Emissivity, Radio Science, InSAR, Topography, and Spectroscopy) comes in. The aim of this mission, which is •

BFLOW
The Maxwell Montes
mountain range on Venus
ncludes the planet's
in ghest point, Skadi Mons



DESTINATION

VENUS

RADIUS: 6,052KM

AVERAGE SURFACE TEMPERATURE: 452°C

SURFACE PRESSURE: 92 BAR



SHURRAYAAN-I

POSSIBLE LAUNCH DATE: 2023

SPACE AGENCY: ISRO (INDIA)

AIM OF MISSION: CRUITER TO STUDY THE SURFACE
AND ATMOSPHERE OF VENUS. POTEN HALLY

INCLUDING RADAR, A PLASMA WAVE DETECTOR

AND A QUOUD MONITORING CAMERA.



VERITAS

POSSIBLE LAUNCH DATE: 2021

SPACE AGENCY: NASA

AIM OF MISSION; ORBITER TO

CAPTURE GLOBAL, HICH-RESOLUTION

MAPS OF TOPOGRAPHY AND ROCK

TYPE ON THE PLANET'S SURFACE



A Y

DAVINCE

POSSIBLE LAUNCH DATE: 2021
SPACE AGENCY: NASA
AIM OF MISSION: DESCENT PROBLETO
UNDERSTAND THE HISTORY OF VENUS'S
ATMOSPHERE AND STUDY THE CHEMICAL
PROCESSES IN THE LOWER ATMOSPHERE.

EXPLORATION OF VENUS: THE HIGHLIGHTS SO FAR

DEC 1962

NASA's Mariner 21s
the first successful
flyby mission of
Venus—or any
planet—sending
back information
about the Venusian
atmosphere.



OCT 1967

Venera 4 is the first successful Soviet mission to Venus. The space probe carries out the trist chemical analysis of the planet's atmosphere revealing it to be mostly carbon dioxide.

JUL 1972

The Soviet
Venera 8 is the
first space probe
to successfully
land on the
surface of Venus
If sends back
lata for 50
minutes.



OCT 1975

to orbit Venus, while it accompanying lander is the tirst to send include of another planet.

DEC 1978

orbiter, carrying out a including mapping the planet's surface and measuring its



EARTH

AVERAGE DISTANCE FROM SUN: 149,600,000KM

RADIUS 6.371KM

MASS: 5.97 × 1024KG

AVERAGE SURFACE TEMPERATURE: 14%

PROPORTION OF CARBON DIOXIDE IN ATMOSPHERE: 0.04 PER CENT

SURFACE PRESSURE 1 01 BAR



POSSIBLE LAUNCH DATE: 2023 SPACE AGENCY: NASA

AIM OF MISSION: SMALL PROVE CAPABLE OF SURVIVING ON THE SURFACE OF VENUS FOR DAYS, CAPTURING INFORMATION ABOUT THE PLANET'S WEATHER.



ENVISION

POSSIBLE LAUNCH DATE: 2032 SPACE AGENCY: ESA AIM OF MISSION: ORRITER TO STUDY VENUS'S ATMOSPHERE, HISTORY AND CLIMATE USING RADAR IMAGING.

VENERA-D

POSSIBLE LAUNCH DATE: 2076 - 2031 SPACE AGENCY: ROSCOSMOS (RUSSIA): AIM OF MISSION: ORBITER, FOR DETAILED **OBSERVATIONS OF THE PLANET'S** ATMOSPHERE; LANDER, TO SPEND AT LEAST TWO HOURS ON THE SURFACE.

IUN 1985

The Soviet space probes Vega 1 and Vega 2 send landers down to Venus, before using the planet's gravity to carry out a flyby of Haney's Comet



AUG 1990

NASA's Magellan spacecraft enters orbit around Venus where it stays for four years carrying out high-resolution radar mapping of the planet's entire surface

APR 2006

ESA's Venus Express enters orbit around Venus, and is the first spacecraft to carry out long term observations of the planet's atmospheric dynamics. It finds evidence for an ozone laver lightning, and a huge, shape-shifting vortex at the planet's south pole



DEC 2015

The Japanese Akatsuki space probe enters orbit around Venus after a previous failed attempt in 2010. It is currently studying the planet's atmosoheric dynamics and cloud structure







 currently being considered for funding by the agency's Discovery Program (a series of lower-cost missions to explore the Solar System), is to use radar and measurements of the planet's thermal properties to produce high-resolution topography maps and information on rock types across the planet's entire surface. This will help to pin down the nature of Venus's volcanic past, but also answer the question of whether it ever had plate tectonics, and what role water played in its history.

Venus's surface has a handful of huge plateaus. "If these features are similar in composition and origin to those on the Earth, it tells us that Venus underwent some very Earth-like processes, and that water was really important in shaping the [Venusian] surface," says Smrekar. She adds that by examining the types of rock on Venus, we could discover whether or not water was once there. For example, certain rock types can only be created when lava meets water. Meanwhile, studying whether Venus's surface is broken up into continent-like features will show whether it once had plate tectonics. On Earth, plate tectonics play an important role in the carbon cycle, helping to remove carbon dioxide from the atmosphere. So a lack of plate tectonics on Venus could help to explain why this planet's atmosphere contains so

ABOVE LEFT

The LLISSE probe. visualised here, is oencilled for launch in 2023 and would be able to survive on Venus's surface

ABOVE

Venus. 1 lustrated here, has the hottest surface of any planet in the Solar System

much carbon dioxide (96.5 per cent), which is in turn responsible for Venus's runaway greenhouse effect.

VERITAS is just one of a suite of missions being proposed to explore Venus. Another in NASA's Discovery Program is DAVINCI (Deep Atmosphere Venus investigation of Noble gases, Chemistry, and Imaging). If selected, this mission would involve dropping a descent probe through the atmosphere and measuring the chemical composition down to the surface in high-fidelity, providing information on the origin and evolution of the Venusian atmosphere, and helping to answer the question of why it's different to that of Earth, DAVINCI lost out to two other missions, Psyche and Lucy, in the 2015 round of proposals, but was resubmitted in July this year.

Meanwhile, another proposed NASA project, not connected to the Discovery Program, is LLISSE (Long-Life In-situ Solar System Explorer). This began in 2017 as a project to develop small landers and instruments capable of surviving on the surface of Venus for days, as opposed to the minutes of previous missions.

"This capability will revolutionise our understanding of Venus by allowing us to see how conditions change over time, giving us new insight into the dynamic processes occurring in Venus's atmosphere," says Dr Lori Glaze, director of NASA's Planetary Science Division, and part of NASA efforts to support LLISSE. "Such information is critical to getting at the history of water and possibly habitable periods in Venus's past. But this requires electronics that can survive temperatures of over 470°C."

Standard, silicon electronics break down quickly under these conditions, so LLISSE would use cutting-edge silicon carbide semiconductors. The aim is to have a probe on the surface of Venus,

"WE NOW HAVE BETTER TOPOGRAPHY MAPS FOR PLUTO THAN WE DO FOR VENUS, SO IT'S TIME FOR AN UPDATE"

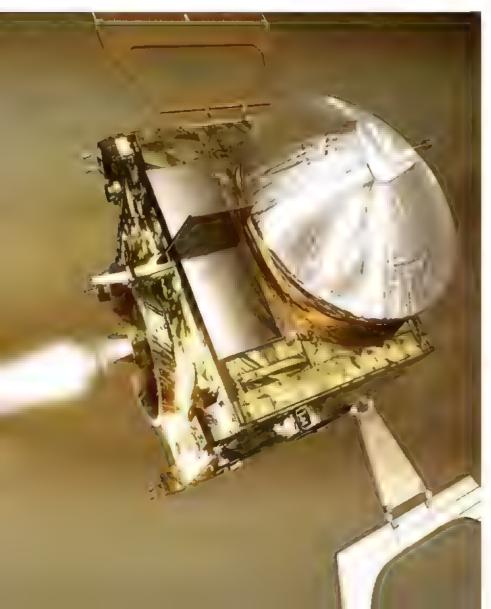
collecting data about the planet's weather in situ – something that would be a breakthrough moment for space exploration.

FUTURE OUTLOOK

Presently, none of these missions are set in stone. Out of all the proposed Solar System missions in NASA's Discovery Program in 2019, five will reach the next stage of development, and one will ultimately go ahead, with a launch slated for 2021. Meanwhile, it's hoped that the LLISSE probe will be ready to go in 2023, likely taken to Venus by another mission.

ESA also wants to study the Venusian surface using radar. The EnVision spacecraft would spend four years orbiting the planet, looking at how much volcanism is taking place and whether the surface is moving, and characterising the interior structure of the planet, too. All of this will help to build a more detailed picture of the differences—and similarities—between Venus and Earth. "It would be really exciting to do real comparisons with Earth," says Ghail, referring to the fact that the Venus data will be of a similar resolution to the geological data we already have for Earth

BELOW
Venus Express, visual sed
here, was the first ESA
miss on to exp ore the
second planet from the Sun



Part of the EnVision mission would include trying to spot the Soviet Venera landers, which sent images of the surface back to Earth. "We want to identify where they are [after they crash-landed on the surface], and then image their immediate surroundings to make sense of the images," says Ghail. This will enable researchers to link the chemistry of the rocks the landers analysed to a specific area on Venus.

EnVision is currently in its first phase of study, which will end in spring 2021. If it is selected, it will launch in 2032, arriving at Venus after a five-month cruise. But NASA and ESA are not the only space agencies with their eyes on Venus. Russia wants to continue its exploration of the planet with Venera-D, a proposed mission which includes an orbiter and a lander. And the Indian Space Research Organisation (ISRO) is planning an orbiter too, called Shukrayaan-1.

All of these missions promise to help us answer the question of how Venus became so different from Earth. But they also have their eye on an even bigger question: is there life elsewhere in the cosmos? Once we have a better idea of the processes that can make a planet habitable, exoplanet hunters will have a better idea of where to look for life on other worlds.

"We need to understand what happened to Venus, and how common this fate is, to estimate how many potentially habitable planets there are," says Prof Abel Méndez, director of the Planetary Habitability Laboratory at the University of Puerto Rico at Arecibo.

More clues will come as astronomers improve their ability to detect and measure exoplanet atmospheres. "We can't tell the Earths from the Venuses right now," says Méndez. A fundamental difference between the two planets is Venus's suffocating, extra-thick atmosphere. This [thickness] is "something we can't measure yet for any Earth-sized planet, but we are getting closer," he says.

Once astronomers have more information about exoplanet atmospheres, they'll be able to combine this with measurements of the planet's distance from its host star in order to gain a better prediction of how likely it is to be habitable. Because, as Earth and Venus have shown, distance isn't everything. "Even Earth with a Venus-like atmosphere would be too hot for life," says Méndez.

It may be a while before we have definitive answers to how many Venuses there are in the cosmos, and why two planets so close to each other could have such vastly different fates, but it seems that the gaze of the world's astronomers is finally turning back towards our closest neighbour. Sometimes, it turns out that the most interesting things are lying right under our noses. **SF**

» **\BIG\II. BI:\LL (@**Jbb/b) 1 Abigoil is a science journalist, based in Leeds.

ESA's Martian rover readies for launch

Ahead of its mission to search for life on the Red Planet, the European Space Agency's Rosalind Franklin rover was sent for a raft of extensive tests in Turin, Italy







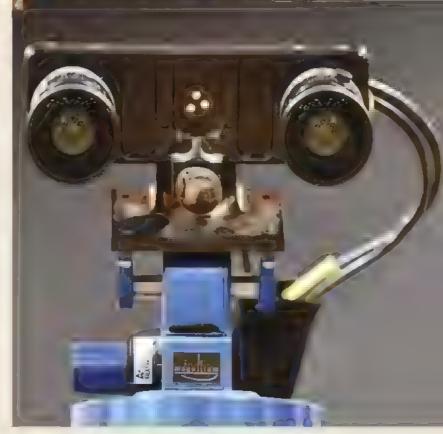


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EYE ON THE SHY

EARTH-BOUND TELESCOPES
ARE TRANSFORMING OUR
UNDERSTANDING OF THE
COSMOS. BUT WE THINK
THEY LOOK PRETTY OUTOF-THIS-WORLD TOO...

PEEK INTO THE PAST

ATACAMA LANGE MILLIMETER/ SUBMILLIMETER ARRAY (ALMA)

Chajnantor plateau, Atacama Desert, Chile

The Atacama Desert in Chile is an astronomer's paradise. Thanks to its high altitude, cold nights, scant precipitation and lack of pollution, it boasts some of the clearest night skies on the planet. That's why the European Southern Observatory (ESO) — an astronomical research organisation of 16 countries — worked with Chile to set up powerful ground-based telescopes in the desert, including the Atacama Large Millimeter/submillimeter Array (ALMA).

Beginning observations in 2011, the high-technelescope consists of 56 precise antennas that can be arranged in different ways to give a variable zoom, capturing sharper detail than the Hubble Space Telescope. ALMA studies light with wavelengths of around a millimetre, originating from the Universe's coldest objects that exist at temperatures at just above absolute zero. These objects include the molecular gas and dust clouds that are the building blocks of galaxies, stars and planets. By studying these regions of the Universe, scientists will be able to decipher the mysteries of planetary formations as well as our cosmic origins.





DECIPHER THE UNIVERSE

VERY LARGE TELESCOPE (VLT)

Cerro Poranal, Atacama Desert, Chile

Around 500 kilometres away on the other side of this desert on Cerro Paranal is the Very Large Telescope (VLT). It consists of four 'unit telescopes' each named after a celestial object in the Mapuche language —spoken by the indigenous population to south-central Chile — and complemented by four moveable 'auxiliary telescopes' just one of the unit telescopes can see objects four billion times fainter than is visible with the human eye. Alternatively, the telescopes can work together to form a huge 'interferometer', allowing astronomers to view much finer detail than is possible by using each telescope individually.

The VLT first started operations in 1998 and has transformed our understanding of the Universe, with its results leading to an average of more than one peer-reviewed paper every day. Some of its most iconic work includes testing Einstein's General Relativity by tracking the movement of a star passing through the gravitational field around the Milky Way's supermassive black hole. However, it has also calculated the age of ancient stars in the NGC 6397 cluster, and has analysed the atmosphere of a super-Earth exoplanet, helping scientists to learn more about worlds beyond our Solar System. The VLT was even able to detect carbon monoxide molecules in a galaxy almost 11 billion light-years away.







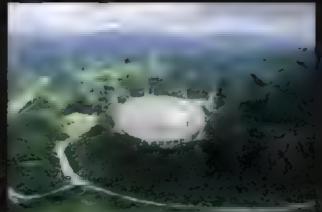
WHAT A DISH!

FIVE-HUNDRED-METER APERTURE SPMERICAL TELESCOPE (FAST)

ngtang County, Guizhou, **China**

On the other side of the world in China's remote and mountainous Pingtang County lies the newest telescope in our roundup, the Five-hundred-meter Aperture Spherical Telescope (FAST). This radio telescope started formal operations in January 2020, andconsists of an enormous 500m-diameter dish composed of 4,450 triangular metal panels that can be adjusted to target different areas. of the sky. The dish focuses incoming radio waves onto a receiving antenna.

It first opened to astronomers in autumn 2019 and is designed to search the skies for pulsars, fast radio bursts (FRBs), and potentially alien life. Pulsars were first spotted by Jocelyn Bell Burnell and Antony Hewish back in the 1960s and were initially dubbed LCMs for 'Little Green Men' until ther were identified as highly magnetised, rapidly rotating neutron stars that can only bedetected by racio telescopes. I have were discovered back in 2007, and are brief, energetic bursts of radio emissions that take place all over the cosmos, however, their precise cause has not yet been identified.









THE CHALLENGING MISSIONS TO HARVEST

The pioneering crafts that will return the largest haul of space dirt to Earth since NASA's final Apollo mission in the 1970s

W LEWIS DARTNELL

SIRIS-REX. Hayabusa2. Make a note of these two names you're going to be hearing a lot about them over the coming months. These spacecraft—one operated by NASA and the other by the Japan Aerospace Exploration Agency, JAXA—have each been orbiting round their own target asteroid. They promise to teach us a great deal about the origins of the Solar System, how we might deflect an asteroid on a collision course with the Karth, and even the molecular origins of earthly life.

Both NASA's OSIRIS-REX and JAXA's

Hayabusa2 are sample return missions

which involved not only touching gently onto their esteroid's surface to collect a scoop of its ancient material, but them noturning it safely back to eagerly waiting ocientists on Earth. This sort of return tripmission within deep space is fabulously complex, and both probes are maryols of engineering. The Japanese probe is a follow up to their earlier asteroid mission, Hayabusa, which naturned a small sample from the asteroid Itokawa in 2010. Despite suffering numerous glitches, Hayabusa racked up a string of accomplishments, including being the first spacecraft designed to land and take off from an asteroid and

"These spore rocks are thought to have delivered a lat of water to primordial Earth"

• the first to return an asteroid sample to Earth. Now on its way home after what is hoped to be a successful mission. Hayabusa2 uses the same basic spacecraft structure as

its predecessor, but incorporates more backup systems to improve reliability, along with some technological advances. As well as upgrades to the communication antenna and guidance systems, Hayabusa2's ion engines are 25 per cent more powerful than its predecessor's, and the probe was able to autonomously control its own final descent to the remote asteroid's surface. Hayabusa2 was also like a mothership in its own right — prior to sampling it deployed a small lander and three rovers onto the asteroid's surface for a closer look, which were able to hop around the landscape to different locations.

Meanwhile, NASA's OSIRIS-REx is the first ever US asteroid sample-return mission. This spacecraft is about twice the size of Hayebusa2 and, rether than using ion engines, it was able to fire standard rocket thrusters to accelerate on its trajectory to its target asteroid, where it is currently in orbit. Both missions have been able to complete a survey of their target asteroids, which included mapping the surfaces and remotely detecting minerals using spectroscopy. Scientists were able to use these results to determine the best spot on their asteroids for Hayabusa2 and OSIRIS-REx to descend to collect their samples.

TIME CAPSULES

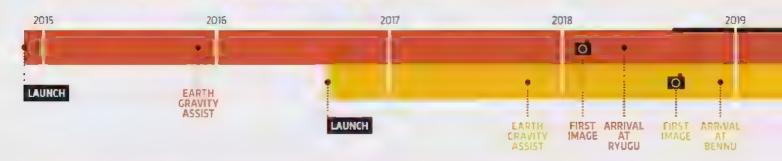
Asteroids are important to study because they represent primordial material left over from the formation of the planets. They are like time capsules from

before the creation of the Earth, preserving matter since the beginning of the Solar System. By studying them up-close, scientists hope to be able to answer some pretty fundamental questions about the formation and development of the Solar System. Specifically, it will help us to understand how planets like the Earth were born, by allowing us to observe the material from which rocky planets form.

Even more excitingly, both the target asteroids for OSIRIS-REx and Hayabusa2 are carbonaceous asteroids. These kind of space rocks have a high percentage of carbon compounds as well as water-containing minerals, and are thought to have delivered a lot of water to the primordial Earth to fill our oceans, along with organic chemicals like amino acids. As Dr Yuichi Tsuda, project manager for Hayabusa2, puts it, "The primary reason we chose our target asteroid is that it is a C-type |carbonrich]. Telescope observations suggest that it should contain lots of carbon as well as water-related minerals, and so give us important clues as to how life on Earth became possible. We've never explored or sampled this type of asteroid before, so these missions are really exciting."



Hayabusa2 & DESIRIE OPERATIONS TIMELINE











ABOVE

Asteroids are time capsules from the Solar System's formation

CENTRE TOP

A recent Image of asteroid Ryugu from Hayabusa2

CENTRE BOTTOM

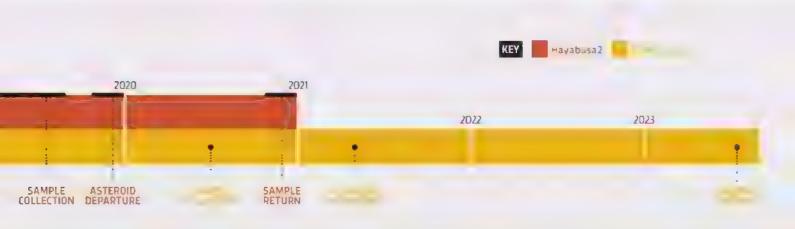
Extracting samples from the first Hayabusa mission upon its return to Earth

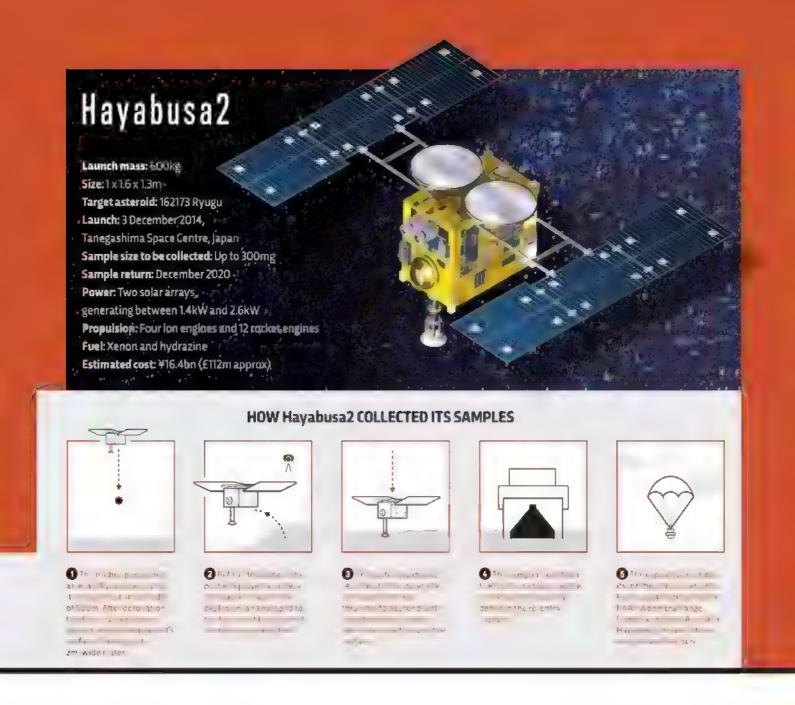
RIGHT

05 RIS-REx being assembled prior to its launch in 2016

Organic chemistry forms the building blocks of all life on Earth. Cells of organisms are made up of certain molecules joined together into long chains: amino acids that build our proteins; nucleotide bases that make DNA and RNA; and the long, oily chains that make up the outer membranes of cells. We know that many of these chemical building blocks are formed in the cosmos - through what is known as 'astrochemistry'- in the cold gas clouds floating through space, as well as the warmer regions around old, dying stars. When this material pulls together under gravity as a new solar system forms, the organic molecules become incorporated into asteroids and comets. So while asteroids don't deliver fully-formed cells to young planets, they may have provided many building blocks for the origin of life - and finding organic molecules on these asteroids would offer support for this idea.

Organic molecules like amino acids have previously been found in meteorites that have landed on the Earth, but these missions will be the first time that scientists will be able to get their hands on carbonaceous material directly from an asteroid. Although meteorites naturally deliver us lumps of primordial space rock, as soon as they land they're susceptible to contamination from Earth's environment. Hence, sample-return missions are important to researchers—material is collected from the source and hurried back via a robotic courier. Prof Sara Russell is a planetary scientist at London's Natural History Museum, and will run some of the preliminary studies on the material returned by OSIRIS-REx. "I've worked •





• on meteorites my whole career, but we're never really sure what sort of asteroid, or where in the Solar System they've come from," she explains. "OSIRIS-REx is like going on a grand field trip to pick our own sample, and when it comes back to Earth in 2023 it will be a meteoriticist's dream come true!"

Both NASA and JAXA chose their target asteroids because they offer pristine carbonaceous material for researchers to study. But they also needed asteroids that are roughly the right size (with enough gravity for their probes to orbit), that aren't spinning too quickly (so that the probes can 'touch down' safely), and that are in a near-Earth orbit that the probes can actually reach. "Asteroids that fit all these criteria are actually quite rare," says Prof Hitoshi Kuninaka, who has been leading the development of Hayabusa2's ion engines. NASA's OSIRIS-REx is orbiting asteroid 101955 Bennu, whereas the

JAXA scientists picked asteroid 162173 Ryugu for their mission. And NASA will collect their samples in a spectacularly audacious way.

OSIRIS-REx will slowly lower itself towards the asteroid's surface, without actually landing, and fold its solar panels upwards to protect them. Here, it will extend a robotic arm and puff a sharp burst of nitrogen gas to blow up particles into its collection head. After just five seconds, the sample collector will close and OSIRIS-REx will automatically begin to back away from the surface. With anything between 60g and 2kg gathered, this precious cargo will be sealed into a re-entry capsule and fired back towards the Earth, where it'll parachute safely to the ground in Utah to be picked up.

Havabusa2 was even more innovative when it collected its samples in 2019. It carried a device called the Small Carry-on Impactor (SCI), consisting of a 2.5kg copper projectile and a shaped



charge of plastic explosive. This explosive fired the copper impactor into Ryugu's surface at over 7,000km/h, blasting out a crater while Hayabusa2 flew around the far side of the asteroid to protect itself from the flying shrapnel. A camera released by the probe watched the impact, transmitting the images to Havabusa2 before the probe returned to the crater to collect its sample. This enabled Hayabusa2 to analyse the interior structure of the asteroid, and gather material untouched by ultraviolet radiation and the solar wind.

Beyond teaching us about the origins of the Earth and the conditions for life, the probes have another critical aim: to help prevent a cataclysmic cosmic collision. As Bennu and Ryugu orbit the Sun close to the Earth, they are exactly the sort of asteroids that present a potential hazard to our planet. The orbit of Bennu, for example, brings it close to the Earth every six years, and it's been calculated that there's a 1 in 1,410 chance that

it might hit us between the years 2169 and 2199

OSIRIS-REx will help us understand how the orbit of asteroids like Bennu might change over time through a process known as the Yarkovsky effect. This is a tiny force caused by the emission of infrared radiation from the Sun-warmed surface of an asteroid, but over long periods it can significantly nudge an object's orbit. OSIRIS-REx is studying this effect and what it means for the probability of Bennu impacting the Earth in the future. The probe is also measuring the asteroid's physical properties. Is it a single body, or perhaps composed of multiple boulders held together only loosely? We'd need to know this before deciding the best deflection technique.

These missions are spectacular both for their audacity, and sheer breadth of their vision. From the origins of life to protecting the life that now clings to survival, the probes promise to offer new insights into our place in the cosmos. SF

a PROLLEWIS DARTNELL

Lewis is an astrobiology researcher at the University of Westminster His latest book Or gins How The Earth Made Js (£9 99 Vintage), is out now



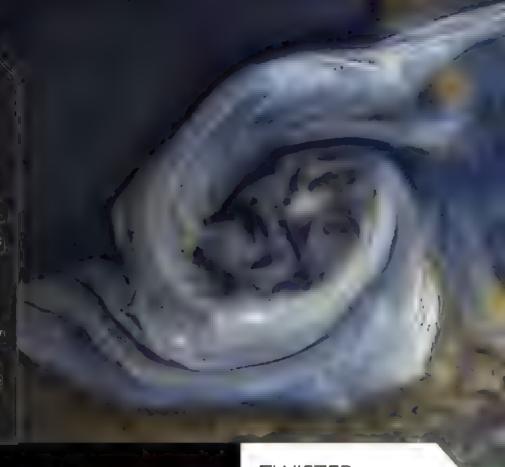


And so it is with the NASA spacecraft of the same name. The secrets of the formation of the whole Solar System lie below Jupiter's all-encompassing clouds, just waiting

to be discovered. Theories about our Solar System formation all begin with the collapse of a giant cloud of gas and dust, otherwise known as a nebula, the majority of which formed the Sun. Like the Sun, Jupiter is mostly hydrogen and helium, so it too must have formed early on, capturing most of the leftover material after our star formed. How this happened, however, is unclear. Did a massive planetary core form first and gravitationally capture all that gas, or did an unstable region collapse inside the nebula, triggering the planet's formation? Once processed, the data taken by Juno's instruments will give researchers insights on how the planet formed and what the conditions in the early Solar System were like. But it also carries an instrument called JunoCam, which has taken a raft of images that so-called citizen scientists from the general public can process, and submit back to NASA. The results have been spectacular.

CLOUDS OF ICE

This reging storm in Jupiter's northern hemisphere was captured during juno's ninth close flyby on 24 October 2017. The image was: taken with the junoCam instrument and processed by citizen scientists Gerald Eichstädtand Seán Doran to enhance the colours to bring out the details in the clouds. The storm is rotating anticlockwise. The brighter clouds are higher inthe atmosphere and catching more light, whereas: the darker clouds are deeper down and so more $_3$ shadowy. In this image, the sunlight is coming from the left-hand side of the Image. Both the bright clouds and their shadows measure from I to 12 kilometres in length and breadth. They appear to be similar to other bright clouds seen by: June, so are probably highly reflective due to ammonia ice crystals that are borne upwards on rising currents of gas from deeper within Jupiter's atmosphere. They may also be mixed with crystals of water ice. Juno took this image from a distance of 10,108 kilometres.



TWISTER

This is what Jupiter's north pole looks like at infrared wavelengths. This composite image has been derived from data collected by the Jovian Infrared Auroral Mapper (JIRAM). These cameras detect temperatures in Jupiter's atmosphere, which roughly correspond to the depth of the cloud features. This image shows the central cyclone at Jupiter's north pole and the eight cyclones that encircle it. Each cyclone is between 2,500 and 2,900 kilometres in width. The colours represent temperatures: yellow shows deeper portions of the atmosphere, which are around -13°C, the darkest areas are higher layers that are a frigid -118°C. Both these regions lie below the visible cloud layer, thus, the JIRAM instrument is giving scientists a way to see into the planet. Finding out how heat flows through Jupiter's atmosphere is vital to understanding the way it works, and provides clues as to how it formed. A key question being investigated is whether the planet has a rocky or metallic core at its centre.



EYES OF THE STORM

Although the Great Red Spot grabs the glorywhen we think about Jupiter's giant storms, it is just one of many that: rage in the planer's atmosphere. This image shows two white storms It was taken by the JunoCam instrument from an altitude of 33,115 kilometres during the ninth flyby of Jupiter on 24 October 2017, and was: processed by Gerald-Eichstädt and Seán Doran. The image is mure colourful than our eyes would see because it has been enhanced to bring out the details in the atmosphere. The storm at the bottom of the-Image is part of Jupiter's 'String of Pearls'. This is all series of oval storms, all of them white in colour, 4 that encircle the planet's: southern hemisphere at a latitude of 40°. Since 1985, the number of storms has varied from six to nine. There are currently eight of these storms, all rotating in an anticlockwise direction These vast storms are being powered by heat; that is generated in Jupiter's Interior.

IUNO MISS ON 9 JUNE 2005 NASA selects juno to become the space agency's neid New Frontiers mission. S AUGUST 2011 Juno launches at 16:25 GMT from Cape Canaveral Air Force Station atop an 🕆 Atlas V rocket... 5 JULY 2016 luno arrives at Jupiter and goes into a polar orbit that varies in altitude from four million to eight million kilometres. 27 AUGUST 2016 Juno completes its first jupiter flyby. All systems and instruments are working well. 19 OCTOBER 2016 Juno is meant to perform an engine burn to reduce its orbit time from 53 to 14 days. Mission managers postpone and ultimately cancel this due to a glitch. 10 JULY 2017 During the seventh close flyby, juno passes over jupiter's mostfamous atmospheric feature, the Great Red Spot. 16 JULY 2018 Juno's nominal mission came to an end but the spacecraft was still healthy, so its operational life was extended. 30 JULY 2021 June will fire its thrusters to decrease its orbit so much that it burns up in Jupiter's atmosphere.

ALIEN AURORA

This infrared image gives an unprecedented view of the southern aurora of Jupiter. The view is a mosaic of three images taken minutes apart as the craft was pulling away from Jupiter, after its first close approach. From Earth, the planet's southern aurora can hardly be seen. It was captured by Juno's Jovian Infrared Auroral Mapper

(JIRAM) on 27 August 2016. Auroras are ovals of light that occur when particles from the Sun strike molecules in a planet's atmosphere and cause them to glow. The auroras appear as ovals because the magnetic field of the planet corrals the solar particles into a cone-shaped funnel that feeds them into the atmosphere around the planet's magnetic poles. The same occurs at Earth, but as Jupiter's magnetic field is the strongest

planetary field in the Solar System – fully 20,000 times stronger than Earth's – its auroras are stronger. This image is composed of wavelengths longer than visible light, ranging from 3.3 to 3.6 micrometres (one micrometre = one-thousandth of a millimetre). These wavelengths were chosen because they are the ones emitted by excited hydrogen ions. These are atoms that have lost an electron particle and dominate the planet's atmosphere.



ON THE SPOT

If you were to compose a list of the seven wonders of the Solar System, Jupiter's Great Red Spot would be near the top. This gigantic storm system is bigger than planet Earth, and rotates in an anticlockwise fashion with a period of about six days. Although a large circular storm has been reported on Jupiter from the 1660s onwards, it may not be the one we see today. Records are poor between 1713 and 1831 and may indicate that the original storm dissipated, and that the Great Red Spot we see today 'only' formed in the 19th Century. This image is an artistic endeavour based on real data. Citizen scientist Gerald Eichstädt used data from the JunoCam instrument and enhanced the colour to draw the eye into the storm. The raw image was taken on 10 July 2017, during Juno's 7th close flyby of the planet. When the image was taken, the craft was about 10,000 kilometres above the planet's cloud tops. SF



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PILUIO BEYOND

After its landmark visit to Pluto, the New Horizons spacecraft continues to revolutionise our view of the outer Solar System

by DR ELIZABETH PEARSON

n 19 January 2006, a spacecraft raced up through the blue skies over Cape Canaveral. By the time it reached space, it was travelling at 16km/s, faster than any launch up until then. The spacecraft was New Horizons. Its destination was Pluto.

It had taken decades for the \$700m (£532m approx) mission to come together. It would be another nine years before it finally reached its target, during which time the International Astronomy Union had demoted the world from 'planet' to 'dwarf planet'.

New Horizons eventually reached Pluto on 14 July 2015. The flyby lasted only a few hours, but in that time the spacecraft took 6.45GB of scientific readings of Pluto and its moons with its cameras, particle sniffers and dust detectors. While it only takes a few minutes to download a file that size to your home computer, transferring the data across the 4.8 billion kilometres between Pluto and Earth

took a little longer - 16 months.

As the spacecraft was sending its trove of data, it continued racing outwards into the region of the Solar System that Pluto calls home – the Kuiper Belt, also known as the Kuiper-Edgeworth Belt.

"The Kuiper Belt is the third region of the Solar System as you move out," says Dr Alan Stern, the principal investigator of New Horizons.

The belt rings our Solar System between 20AU to 50AU (1AU is the distance between the Earth and Sun), and is filled with large icy bodies called Kuiper Belt Objects (KBOs). At 1,188km across, Pluto is one of the largest KBOs, but there are an estimated 35,000 space rocks floating through the region. They are thought to be the leftovers from when the planets formed and represent the most pristine example of the primordial nebula from which our Solar System was born. By studying these ice-rocks, planetary scientists hope to gain a better understanding of the conditions in which •

"It is the first spacecraft to pass through these outer regions of our Solar System since the Voyager probes"

• the planets grew.

Before the flyby of New Horizons, the only view we'd seen of these icy bodies were comets, many

of which are thought to have originated in the Kuiper Belt before being knocked inwards. But while comets have been warmed and changed by the Sun, New Horizons offered the first chance to look at these worlds close-up in their natural habitat, and the researchers weren't going to be happy with looking at just Pluto.

It would only take a little nudge to send New Horizons towards another target. But first, the team needed to find one. Fully surveying the New Horizons flight path for KBOs took several years, but in 2014 they found one – Arrokoth (previously nicknamed Ultima Thule).

MASS APPEAL

From what we know of the Kuiper Belt via longrange observations, Arrokoth is much more typical of other KBOs in terms of its size and colour than Pluto. A flyby would give a far more representative look at what a body in the Kuiper Belt looks like.

Despite the difficulties in aiming at a world just 36km long and over 6.6 billion kilometres away, New Horizons successfully sped past on New Year's Day 2019. The data download from Arrokoth will take until 2021, but it's already yielding momentous results. Arrokoth is what's known as a 'contact binary', meaning it's formed from two separate bodies that have stuck together. It is thought that the planets in the Solar System grew from small space rocks that clumped together to ever increasing sizes, so Arrokoth is the perfect place to test theories about how this process worked.

"There are two basic theories of how small bodies formed in the Solar System," says Stern. "One says they formed from the collision of bodies from distant regions of the Solar System. The other theory says they form from objects only made locally around themselves in what's called the 'cloud collapse model'. We can determine that the local cloud collapse model fits with the geology of Arrokoth, deciding a long-

standing scientific controversy between the two theories of how the planets form."

There is still much for New Horizons to do beyond simply sending its data, however. There's a chance for another flyby and Stern's team are preparing a hunt for more potential targets. Once again, the search will take several years — until at least 2022 — but this time, the flight team are working against the clock.

"The Kuiper Belt only runs out a finite distance," says Stern. "By 2027 or 2028 we will exit the Kuiper Belt. We must find and intercept an object by that date or we will be past the Kuiper Belt and the possibility of a flyby will end."

If these searches do come up empty, the mission is still far from over. It is the first spacecraft to pass through these outer regions of our Solar System since the Voyager probes. Updated with 30 years' worth of technological advancements, New Horizons can look for things that the Voyagers could not.

"We've already seen evidence of a vast structure of hydrogen gas in the outer Solar System," says Stern. It was predicted decades ago but was never observed until New Horizons. "We also observed pick-up ions. These are atoms from interstellar space that have become part of the heliosphere – the environment of the Solar System. Again, they have been predicted for many years, but Voyager didn't have the right spectral range to discover them "

The spacecraft is also carrying the first ever dust detector to travel beyond the orbit of Uranus, allowing the New Horizons team to map the distribution of dust in the Kuiper Belt. The researchers are watching to see if particles smoothly tail off towards the edge of the disc, or if they suddenly drop off.



Visualisation of the trans-Neptunian object, contact b nary Arrowoth the most distant object visited by a human spacecraft.

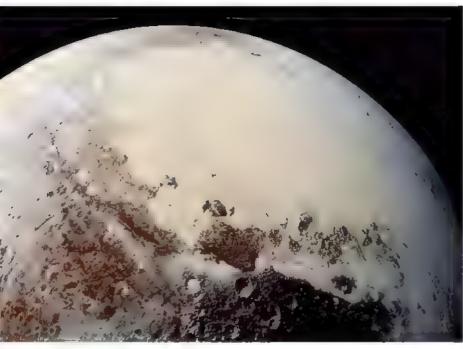
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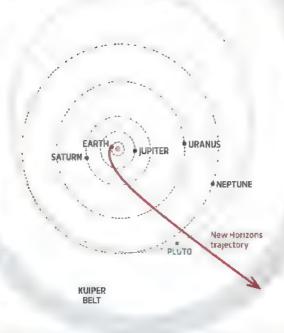
Pluto's 'Brill ant Heart' is rich in rich in mitrogen, carbon monox de and methane ices. The western lobe is captured here by New Horizons

FAR RIGHT

Overhead view of the New Horizons trajectory through the Solar System as it entered the Kuiper Be t









140 A K . U

smoothness.

atoms from interstellar space.



There are plenty of scientific communities clamouring to use the spacecraft to observe this seldom visited region. For the time being this research is limited, as Stern wants to preserve the fuel in case another flyby presents itself.

"I often call myself 'fuel hoarder in chief'," says Stern. "There's only so much fuel in the tank. If we discover a flyby but can't reach it because we used part of the fuel for other purposes, that would be scientifically tragic."

If there is no third Kuiper Belt flyby, or there's still fuel left after it, then the spacecraft's cameras could be pointed back at the inner Solar System to give a unique view of the planets, comets and asteroids from the outside New Horizons is also outside of the dusty environment of the inner Solar System, and so its instruments could be pointed towards the wider Universe to take advantage of the clear view of distant objects across the void of space.

TIME IS RUNNING OUT

But no one lives forever, and neither does a spacecraft. The nuclear power source on New Horizons is only expected to last another 20 years. Travelling at around 500 million kilometres per year (about the distance from Earth to Jupiter), it should be out at around 100AU by this point,

"If we discover a flyby but can't reach it because we used the fuel for other purposes, that would be scientifically tragic"

> meaning the team will aim to investigate one final region before the spacecraft dies - the outskirts of the heliosphere. New Horizons is unlikely to reach the very edge, as the Voyager probes found it is located around 120AU out, but there is a chance the spacecraft could make it.

> "The boundary between the heliosphere and interstellar space breathes in and out because of the Sun's 11-year cycle of activity," says Stern. "We know where New Horizons will be very accurately but we don't know where the boundary is. If it's closer, we'll cross it. If it's further out, we'll run out of power."

> What exactly New Horizons will do with the rest of its time is uncertain, but it is clear that with fuel left in the tank and 20 years on the battery, its mission is far from over. SF

& DR ELIZABETH PEARSON LE 27 Elizobeth is a space

journalist and news editor at BBC Sky At Night magazine

QUICK FACTS

CAUMIN OWNER

Voyager 1: 5 Sept 1977 Voyager 2: 20 Aug 1977

DISTANCE TRAVELLED AS OF JANUARY 2020: V7. 22 246,465 086km. **V**2 18.483 483,599km

DISTANCE FROM THE SUN AS OF JANUARY 2020 VT: 22.144 959.920km VZ 18,365.602,503km

FINAL MISSION PURPOSE:

The Voyager Interstellar Mission (VIM) aims to extend the NASA exploration of the Solar System to the outer limits of the Sunis sphere of influence and beyond

INTO THE UNKNOWN

or 40 years, the twin Voyager

The twin Voyager probes are now exploring interstellar space

by DR ELIZABETH PEARSON

spacecraft have sailed through our. Solar System, pushing, humanity's knowledge of the cosmos ever outward. Launched in 1977, the probes took advantage of a rare, alignment of the outer planets (Jupiter, Saturn, Uranus and Neptune); flying past Jupiter in 1979, before travelling onto Saturn in the early 1980s. Voyager 1 took a detour for a closer look at the rings, but this swing its proit northwards out of the plane of the planets. Voyager 2 carried on alone, flying past Uranus in 1986 and Neptune in 1989, marking the end-

of Voyager's planetary mission.

But it also marked the start of Voyager's next phase, the interstellar mission to investigate the outer regions of the Sun's heliosphere. "The heliosphere is the bubble created by the solar wind," says Ed Stone, Voyager's project scientist since 1972. "The solar wind is travelling from the Sun at supersonic speeds, around 400km/s, and we knew at some point had to run into the interstellar wind,"

Voyager 1 was the first to reach the edge of the heliosphere, known as the heliopause, in August 2012. When it was 150 million kilometres from the Sun (about 120 times the Earth-Sun distance), the spacecraft detected an

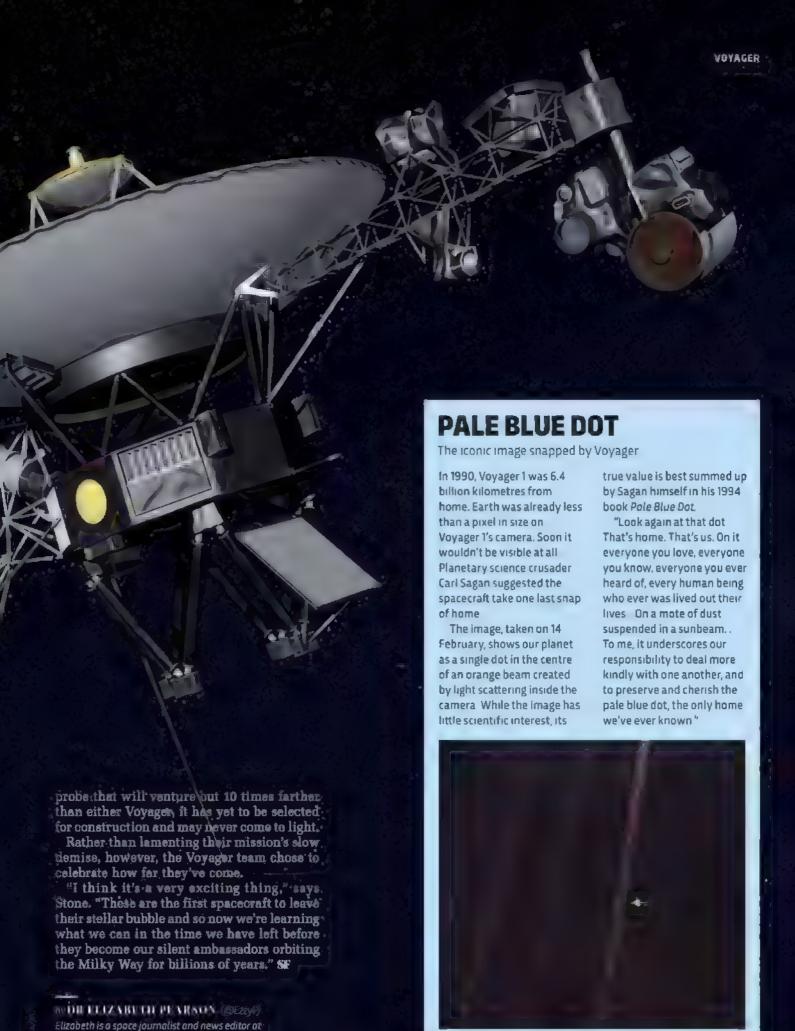
uptick in the number of particles originating from other stars. Voyager 2 followed suit in November 2018 when it was roughly the same distance out.

The Voyagers are now taking humanity in first in-situ look at the cosmos beyond our local solar neighbourhood, but at more than 40 years old, the spacecraft are feeling their age. By modern standards, their instruments are simple and only capable of basic measurements of particle energies and magnetic field strength and direction. To make matters worse, the Voyager's nuclear generators are running out of power, forcing the team to shut down instruments to conserve energy. Even so, they only expect the mission to last another five to 10 years.

"From an engineering point of view, it's a new phase of the mission. We have to operate the spacecraft in conditions it was never designed for. We are doing all we can to extend our knowledge as far out into interstellar space as possible but leave it for some future mission to go further," says Stone.

to go further," says Stone.
So far, only New Horizons, which flew past
Pluto on 14 July 2015, has picked up that baton.
It too is heading towards the heliopause, but
its own power source might also give out
soon. Though there are ideas for an interstellar

After completing, their primary, mission to explore jupiter and Saturn, the two Voyager probes are continuing into interstellar space.



BBC Sky At Night magazine:





ook up at the night sky and find the famous three stars of Orion's Belt. Then extend the line between them upand to the right towards the constellation of Taurus. The Bull. Halfway between them sits a small patch of otherwise unremarkable sky that could well be home to one of the most famous finds in astronomical history – aninth planet orbiting the Sun. It isn't every day a newplanet is discovered in the Solar System. In fact, by one measure, it has only happened twice before in all of human history with Uranus (1781) and Neptune (1848). All the other planets have been known since antiquity and were neverreally 'discovered'. Objects:

such as Ceres (the largest asteroid) and Pluto were once deemed part of the planet club, but have since had their membership revoked. William Herschel, Urbain Le Verrier, Johann Gottfried Galle and John Couch Adams are the only astronomers to ever find a new planet that is still considered as such.

That elite list may soon be about to grow. Callech astronomers Mike Brown and Konstantin Batyginare among the frontrunners to join it. Back in-2016 they went public with the radical notion that the roll call of planets orbiting the Sun iso't finished. They had noticed a handful of small worlds beyond Neptune behaving mysteriously, and considered that perhaps a ninth planet could account for their strange motion. "We were confident that another planet could explain the features of the outer Solar System," says Batygin. They've been scenning the sky for this object, but so far it has escaped them. For mow, this potential world goes by the moniker of Planet-Nine. If and when it is discovered, it will be mamed after a Roman or Greek deity, just like the other planets.

LONG-DISTANCE RELATIONSHIP

Planet Nine's suggested existence is based on observations over the last decade with telescopes big enough to peer into the murky environs: beyond the eight known planets. Studying this under-explored wilderness is a real challenge. We only see thanks to reflected sunlight, and for these trans-Neptunian objects (TNOs) that light has to undergo quite a journey. The odyssey starts at the Sun, then travels out to a distance of more than 4,500,000,000km, before bouncing off an object and making the return trip to the Earth almost all the way back to the start. That light is also fading all the white, making it very faint and requiring a big telescope to collect it. Take the 600-kilometre-wide object known as 2012 VP113. It sits 80 times further from the Sun than the Earth, meaning the light we see reflected from it is around 40 million times dimmer than normal sunlight. Despite travelling at 300,000 kilemetres per second, light takes nearly a day to cover the full distance from the Sun to VP113, and back to the Earth.





It was the discovery of VP113 by astronomers Scott Sheppard and Chad Trujillo in 2014 that first flagged up the possibility of an undiscovered planet. They are another team currently hunting down Planet Nine, Closer scrutiny of VP1.13's path around the Sun showed that it shared orbital characteristics with another TNO called Sedna: The angle at which they approach the Sun is eerily similar. Our best theories of Solar System formation say that for each object this tilt should be random. So the fact that these two objects match arouses suspicion. "They're like the fingerprints and broken glass of a crime scene," says Megan : Schwamb from the Gemini Observatory in Hawaii and co-discoverer of several TNOs. "Who did it?". One explanation is to point the finger at $oldsymbol{a}_{r}$ ninth planet, whose gravity is pulling on these objects and organising their orbits. To be doing that it would have to be several times the massof the Earth. It wouldn't be the first time we'vefound a new planet this way. After Uranus was discovered, discrepancies in its orbit were put down to the tug of another planet even further out: Sure enough, when astronomers calculated where this planet would be they discovered Neptune. Now teams of astronomers including Brown, Batygin, Sheppard and Trujillo are trying to do the same with Planet Nine ...

HIDE AND SEEK

So far the planet remains stubbornly out of view, but the search has cemented the evidence that it is really there. In the process of trawling the outer Solar System, astronomers have uncovered new TNOs. We now know of 14 objects clustered tegether more than 230 times further from the Sun-

than the Earth. This includes an object otokoamed The Goblin, discovered by a team of astronomers including Sheppard and announced in October 2018. It's a 300-kilometre-wide TNO on a highly elongated 40,000-year loop around the Sun. The more of these objects that we find sharing similar tilts, the stronger the case for Planet Nine becomes.

But there are alternative explanations. The leading one is that these copycat orbits are nothing more than observational bias. There are thought to be millions of TNOs out there that we haven't found yet, all with ©

POP: The free confirmed density planets in our Solar System and their meens. From left to right Plate; Erris; Malanmalor; Sandalor, Heatman

MIDIAL: Pheragion of sky between Orion's Belt (yallow circle) and Tannia (white circle) is the search area. for Planet Mine.

MOTTONS
Action to
Action to Management Mines

FAMOUS OBJECTS BEYOND NEPTUNE



SEDNA

Discovered by Mike Brown, Chad Trujillo and David Rabinowitz in 2003, Sedna was one of the objects that forced astronomers to re-evaluate Pluto's planethood. It takes 11,400 years to orbit the Sun, crawling along at an average speed of just one kilometre per second Sedna will make its closest approach to the Sun in 2075–2076, providing a once in an 11,400-year opportunity to get the best view of this world named after the Inuit goddess of the sea



2012 V<u>P113</u>

This object is often in cknamed Biden' after, oe Biden who was the US vice president at the time of its discovery at the Cerro Tololo Inter-American Observatory in Chile. At 600 kilometres wide, astronomers believe its pink colouration is due to the way cosmic radiation has shaded its surface which is made of water and/or methane ice. It doesn't get as close to the Sun as Sedna, nor as far away. Sedna and Biden were the onginal basis for the Planet Nine idea.

O random orbits. It could just be a fluke that we've happened upon the handful that do share similar paths around the Sun. If this were true. Planet Nine would be a figment of our imaginations. But in January 2019 Brown and Batygin published new research attempting to quantify how likely this is based on the latest TNO discoveries. Their answer? Just 0.2 percent. "That's our most conservative estimate," says Batygin. A ninth planet, they claim, is the only existing explanation for what we see in the outer Solar System.

SCOURING THE SKIES

That doesn't mean finding it is easy. All searches so far have failed to spot the planet. The bont is not helped by the fact that there are only a bondful of telescopes in the world capable of seeing it. Not only do you need a large aperture telescope to collect the faint light, you also need

one equipped with a camera with a wide field of view. Brown is using the 8.2-metre Subara-telescope in Hawali to bunt for it, while Hatygin is busy crunching the numbers. "The search area is \$00 square degrees of sky," says Brown. That's about the same as 3,200 full Moons. A telescope with a marrow view would just take too long to cover this vast expanse.

It's not a two-dimensional patch of sky either, but three-dimensional. We also don't know Planet Nine's exact distance from the Sun. If it is near it will be brighter and if it's further away it will be dicamer. When it comes to the brighter end, Brown says they've already covered nearly all of the sky where it might be hiding without success. "That's surprising to me," he says, "That would have been the most reasonable guess of what Planet Nine would be like."

The findings are all the more unexpected when Batygin's latest computer modelling is ©

"A NINTH PLANET, THEY CLAIM, IS THE ONLY EXISTING EXPLANATION FOR WHAT WE SEE IN THE OUTER SOLAR SYSTEM"



THE GOBLIN

Named because it was discovered close to Halloween. The Gobilin was first observed on 13 October 2015 using the Mauna Kea Observatory in Hawaii. It took three years to track it in sufficient detail to pin down its orbit and announce the discovery to the public. The Gobilin's highly elongated orbit carries it from roughly twice. Puto's distance from the Sun all the way out to 30 times further than that it's about as bright as one of Piuto's smaller moons.



FAROUT

Astronomers like to keep things simple where they can, as illustrated by the nickname of this object found on 10 November 2018. A name like FarOut marks that, at the time of its discovery, it was the furthest object ever found in the Solar System. Unfortunately this wasn't kept as its official name, and it became. 2018 VG18. Looking back at older photographs actually shows that FarOut had been captured before in 2015 and 2017. Like VP113, it appears to be pinkish in colour.



EARFAROUT

FarOut didn't hold its crown as a record breaker for tong. In February 2019 a team led by Scott Sheppard announced the discovery of an object even further out - nicknamed FarFarOut. This tame it is 140 times further from the Sun than Earth (or 21 billion kilometres). Both objects have been found so recently that their orbits are still being determined to see if they support the Planet Nine theory.





taken into account. "We've performed thousands of new computer simulations in the last 18 months," he says, all to understand more about where Planet Nine could be. According to Batygin, the upshot of those calculations is that "Planet Nine is smaller in all parameters by a factor of two compared to our original estimates". Its orbital period is now thought to be 10,000 years rather than 20,000. It is five times the mass of the

Earth, not 10. Despite being smaller, its shorter orbit would make it about two and half times brighter than the original 2016 estimates

THE NET IS CLOSING

So how come Brown still hasn't found it, despite trawling the whole area at the brighter end? "We don't know its albedo and that's the key parameter," says Brown. Anobject's albedo is a measure of how much sunlight its surface. reflects back into space. "It could either be a super-cloudy, bright object or a dark ice ball covered in junk with a lowalbedo." The fact it hasn't been found yet suggests it is: the latter. If a dull surface is making it dimmer, finding Planet Nine will take more time. "We've covered about 58 per cent of the sky in that range," he says:-

So the net is closing, but it is a laborious process. "The main difficulty is sustaining such an intense search formany years," says Brown. Planet Nine's predicted position out between Orion's Belt and Taurus is both a blessing and curse. Orion is part of the winter sky, which means that astronomers are restricted to searching for it during that season. In the summer it is part of the daytime sky and therefore undetectable. On the plus side, winter nights are longer, but the emphatic downside is that in recent years. the winter weather in Hawaii has been horrendous. Batygin recalls one occasion where he was driving up the volcano to --- almost certainly this missing the telescope with hailstones the size of golf balls slamming into the car. On another occasion the weather looked clear, but Brown arrived at the telescope to find the door to the telescope was frozen shut. "We've had every sort of obstacle you can imagine," says Brown. Other roadblocks have included volcanic eruptions, earthquakes and

sulphur dioxide fumes. "It's frustrating," he says. "[I'd] like to find it and move on to something else." With winter drawing to a close, the season is almost done and the search will soon have to wait until the Earth moves back round to the favourable side of the Sun.4 Batygin sums it up nicelys: "Nature has no obligation to you," he says. "Look atgravitational waves - they took 100 years to find. " If the current searches fail, i there's hope on the horizon

in the form of the Large Synoptic Survey Telescope (LSST).. Currently under construction in Chile, its 3.2 billion pixel camera will be capable of photographing an area of sky the size of 49 full Moons at once. It's due to start operation in 2022. Even if it doesn't find Planet Nine right away, it is expected to discover hundreds of new TNOs. If their orbits also share the tell-tale alignment, then that would both strengthen the case for Planet Nine and point astronomers towards where to find it. According to Schwamb, the Planet Nine hypothesis is an answerable question. "It is not going to be a mystery forever," she says.

A deeper puzzle is how Planet Nine got there in the first place. How does a planet five times the mass of the Earth end up marooned up to 20 times further from the Sun than Neptune? The most likely explanation is it formed in the inner Solar System with the other eight planets. before some event threw it out into the depths of space. Even before astronomers found evidence for Planet Nine computer simulations of the Solar System's formation were hinting at a missing planet. Starting with five giant planets resulted in a Solar System that looks more like ours today. than if it started with just four. The only trouble was that there was no other evidence that this extra planet everexisted. Yet if the current frenzy of activity confirms the

existence of Planet Nine, it is 🔻 world, Its discovery would mean more than just another planet on the list; if could be the key to understanding why our Solar System looks: the way it does today. SF

TOLIN STUART Colin is an astronomy author. Get this weekly space newsletter of colinstuart.net/newsletter:

WATCHING

WHETHER DEEP UNDERGROUND OR PERCHED ON A VOLCANO, PARTICLE DETECTORS HELP SCIENTISTS TO UNRAVEL THE MYSTERIES OF THE COSMOS N BRIAN CLEGG

DETECTORS

STRIKING GOLD

→ PROTODUNE, FRENCH-SWISS BORDER

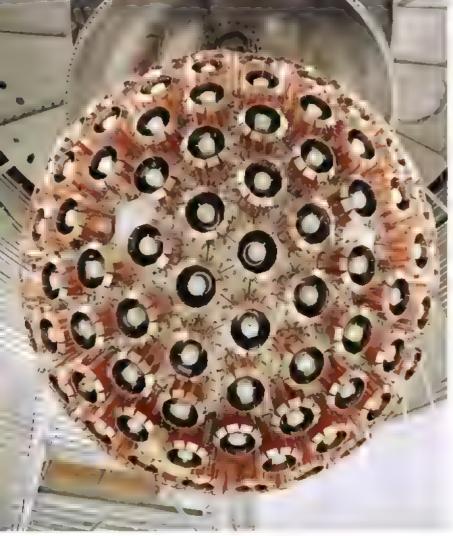
DETECTING NEUTRINOS

Bathed in yellow light to avoid overstimulating its sensors this neutrino detector is the size of a three-storey house. Neutrinos are abundant - trillions pass through you every second - but they hardly interact with matter, making them tough to detect. When in operation, ProtoDUNE is filled with 800 tonnes of liquid argon. Sometimes, a neutrino makes a direct hit on an argon nucleus, producing a trail of charged particles detected by grids of wires around the detector. This prototype is being tested at CERN's headquarters, but DUNE (Deep Underground Neutrino Experiment) will be sited 1.5km underground in the disused Homestake gold mine in Lead, South Dakota. With four detectors, DUNE will pick up neutrinos generated by a particle accelerator 1,300km away at Fermilab, near Chicago. Expected to go live in 2026, DUNE will detect differences in behaviour between neutrinos and their antimatter counterpart, antineutrinos, which could help explain why the Universe has more matter than antimatter.









TANKS A LOT

← HAWC (HICH-ALTITUDE WATER CHERENKOV OBSERVATORY), MEXICO

DETECTING GAMMA RAYS

In the shadow of Mexico's Pico de Orizaba volcano, these 300 steel tanks make up the HAWC, which is on the lookout for gamma rays – high-energy radiation created by cataclysmic events in space. When gamma rays hit our atmosphere, they produce a shower of fast-moving particles, which can interact with water molecules to create 'Cherenkov radiation', visible as an eerie glow. Each of the 7m-wide tanks is filled with water, plus detectors for picking up the radiation. HAWC has recently been used to study the SS 433 microquasar, around 15,000 light-years away. SS 433 consists of a black hole consuming a star, pushing out jets of matter that generate gamma rays.

CATCHING WAVES

→ LIGO (LASER INTERFEROMETER GRAVITATIONAL-WAVE OBSERVATORY), USA

DETECTING GRAVITATIONAL WAVES

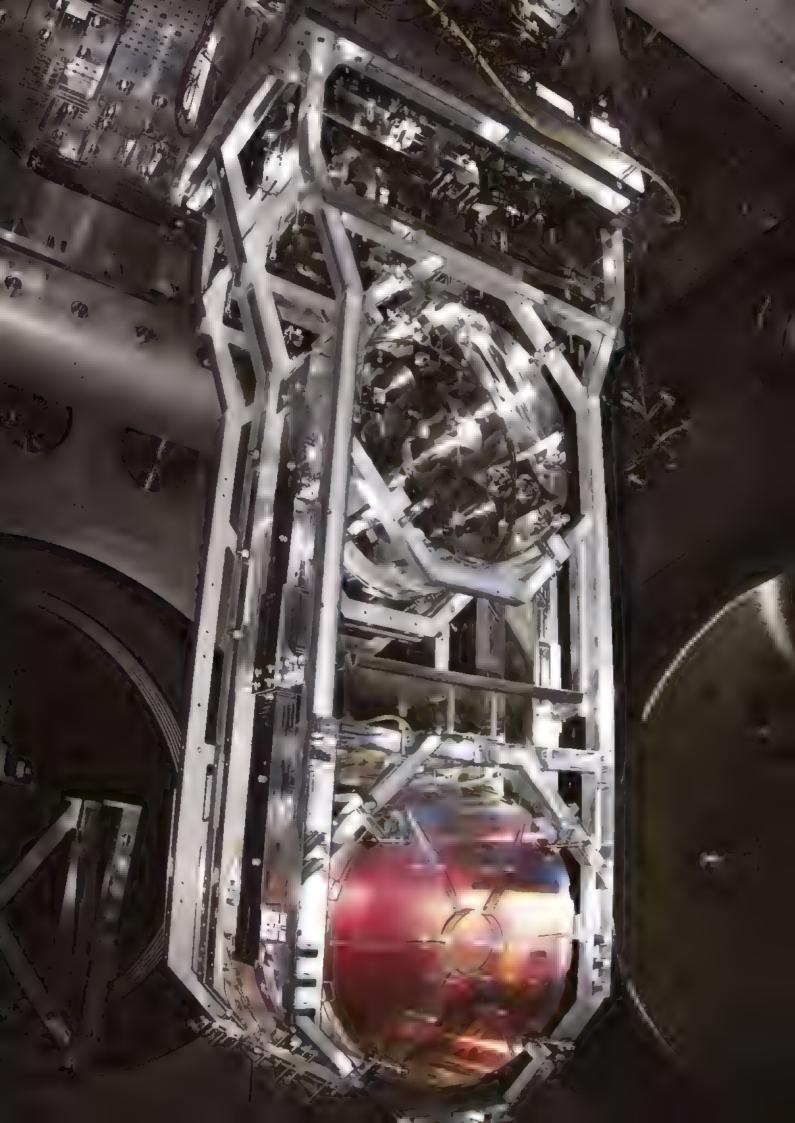
This 40kg, red-tinted mirror is suspended by an elaborate system, allowing it to detect movements smaller than an atomic nucleus, indicating the arrival of gravitational waves. Comprising two sites over 3,000km apart, each LIGO site has a pair of 4km-long tubes, through which lasers repeatedly travel, revealing movements in these mirrors. On 14 September 2015, astronomy was changed forever by LIGO's first detection of gravitational waves. Predicted by Einstein in 1916, these vibrations in the fabric of space-time are caused by cosmic collisions like merging black holes. So far, LIGO has detected 11 black hole and neutron star mergers.

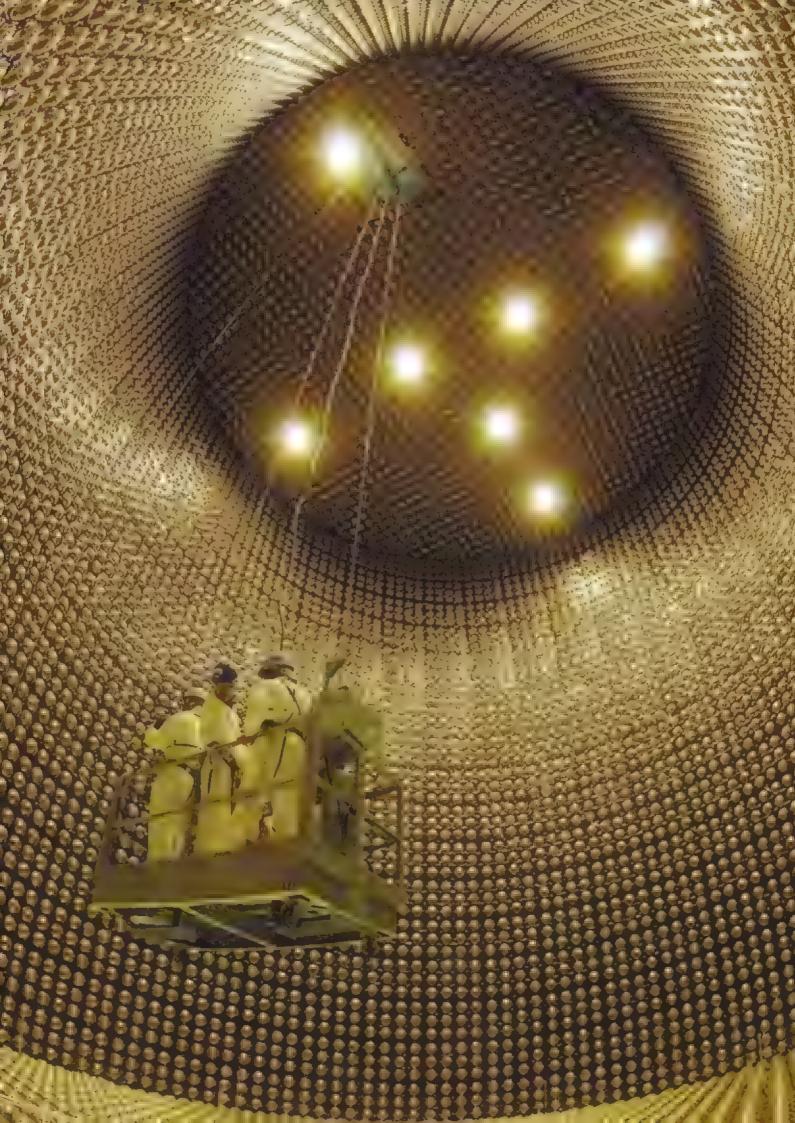
DEEP, DARK SECRET

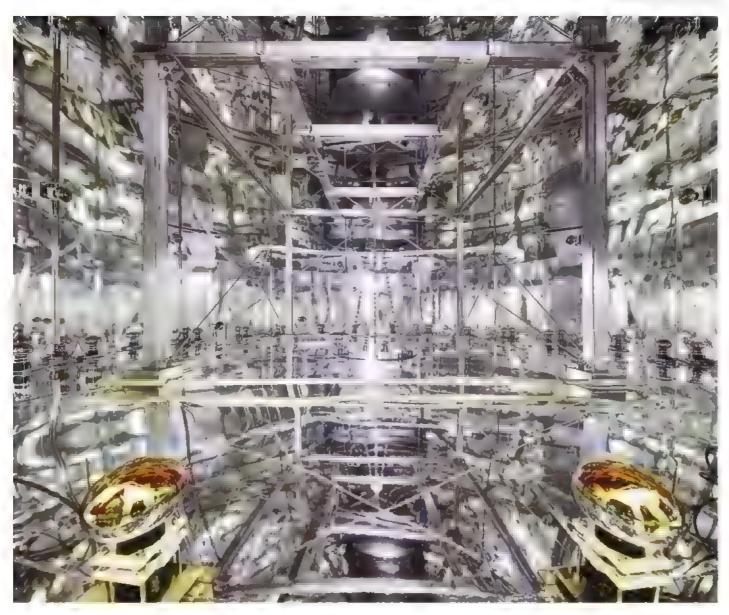
← DEAP-3600 (DARK MATTER EXPERIMENT USING ARGON PULSE-SHAPE), CANADA

DETECTING DARK MATTER

This flower-like array of photomultiplier tubes in the DEAP-3600 detector surrounds a chamber of liquid argon. The tubes are pointed inwards, looking for tiny flashes of light as incoming dark matter particles interact with the argon nuclei. Dark matter—predicted by measurements that galaxies seem to contain far more matter than is observed—should outnumber ordinary matter particles five to one. One theory is that dark matter is made of WIMPs ('weakly interacting massive particles'), which is what DEAP-3600 is looking for. To reduce interference, the detector is located 2km underground in an old nickel mine at Sudbury, Ontario. DEAP-3600 began operations in 2016, and the first data is just starting to be analysed. So far, nothing has been found.







LIGHT SHOW

← SUPER-KAMIOKANDE, JAPAN

DETECTING NEUTRINGS

Over 13,000 light-detecting tubes line the Super-Kamiokande neutrino detector, 1km beneath Mount Ikeno in Japan. The 40m-wide tank holds 50,000 tonnes of pure water. When neutrinos collide with the water molecules, they produce fast-moving electrons, generating Cherenkov radiation, detected by the tubes in this photo. Super-Kamiokande has been central to our understanding of neutrinos' weird behaviour. We know that the Sun produces vast quantities of neutrinos, but only about a third of them were being detected. Super-Kamiokande, along with Canada's Sudbury Neutrino Observatory, was used to show that neutrinos go through a process called oscillation, shifting between three different types in flight - which explained why so many were going undetected. This showed that - contrary to expectations at the time neutrinos have mass, flagging up a gap in our understanding of how the Universe works

↑ XENONIT. ITALY

DETECTING DARK MATTER

In operation, the 10m-high outer chamber of XENON1T is filled with water, which shields the central part of the experiment from contaminating particles and radiation. Inside this water chamber sits a super-low temperature fridge, known as a cryostat, which houses 3.5 tonnes of liquid xenon. Situated at the underground Gran Sasso lab in Italy, the aim of this experiment is to spot collisions between xenon atoms and hypothetical dark matter particles known as WIMPs. When xenon atoms and WIMPs collide. they should produce faint flashes of light. The first results from XENON1T were released in 2017, and as yet no WIMPs have been detected. The researchers are building the next phase of the experiment -XENONnT - which will contain eight tonnes of xenon (giving a greater chance of a collision being observed), and is designed to be more sensitive, thanks to lower background radiation. SF

S BRIAN CLEGG

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Brian is a science writer who has authored more than 30 books. His latest is Scientifica Historica (£25, Ivy Press), is out now.



THE HUNT FOR EXOPLANETS

Over the coming years, a new generation of space telescopes will seek out distant planets in the hope of unlocking the secrets of the Universe

WIAIN TODD

n January 1992, two radio astronomers announced a discovery that would change our view of the Universe forever. Aleksander Wolszczan had been scanning the akies to study a type of spinning star known as a pulsar, but something was blocking his view. Curiosity piqued, Wolszczan eventually discovered the root of the interference: two planets in orbitaround the star. Fellow radio astronomer Dale Freil verified the data, and the pair made their incredible announcement to the world: they had discovered the first eyer known extra solar planets — or 'exoplanets'.

The existence of exoplanets—planets orbiting stars other than our Sun—had long been theorised, but now there was definitive proof. For the first time, humanity could be sure that the Solan System in which it lived was not alone; there were planetary systems out there in the cosmon

Since this discovery, there has been a concerted affort by astronomers to find even more of these exopianets. NASA's Kepler Space Telescope lamp had in 2009, has confirmed more than 2,300 exoplanets, and revealed that; on average, there is one planet orbiting every star. The next time you look up at the night sky, think about this: for every star you can see, there is probably another world in orbit around it.

Now, a new generation of exoplanet-hunting missions is primed for follow-up investigations to build on Kepler's progress and make discovering that could change what we know about how planets form, and how life might arise elsewhere in the Universe.



Perhaps most exciting is the James Webb Spaces Telescope (JWST). This orbiting observatory, due to launch in 2021, is expected to make many new discoveries, including the search for exoplanets JWST is seen by many as the successor to the Hubble Space Telescope, albeit 100 times as powerful and, rather than orbiting Earth, will instead orbit the Sun at a distance of 1.5 million-kilometres from our planet. This will help it avoid heat from the Sun, Earth and the Moonand remain cool—around -225°C; Why? Because warm objects emit infrared light, and infrared will be JWST's primary method of observing the Universe.

One of its goals will be to observe young planets forming around young stars. Stellar formation begins when clouds of gas and dust in space begin to clump mass together, growing so big that they eventually collapse under their own gravity. What remains is a young proto-star surrounded by a spinning disc of dust. Out of this dust may form a system of planets orbiting the central star, just like our own Solar System. In optical light these still-forming planets are obscured by the dust, but infrared can peer through it to get an amprovedented look at planetary formation in action.

We build space telescopes because they can also sharper pictures, due to the fact that Earth's temosphere is not in the way distorting what we're trying to see," says Dr Jane Rigby, one of the mission's project scientists. "If we want study most colours of infrared light, then seeneed to go into space because that light of



annot shine through our atmosphere."

What's really exciting is JWST's ability to split starlight, a technique known as 'spectroscopy'. By splitting the starlight that has passed through the atmosphere of an exoplanet, scientists can analyse the chemical signatures hidden within and learn much about the properties of that exoplanet - whether it has a lot of water vapour in it, for example, or other chemicals that might reveal something about the processes occurring on its surface.

"For gas giants like Jupiter and Saturn around other stars, we can look at bands of methane to see whether the atmosphere has clouds or whother it is clear," says Rigby. "This is our first chance to understand in detail the atmospheres of exoplanets, and there's a lot of interest in studying rocky planets like our own."

If we are to understand how our Sun, the Earth and the other planets formed, we need to look for examples of planetary formation in action. Until relatively recently, we only had one frame of reference: our own Solar System. Now, we have a wide variety of different stars and orbiting exoplanets to choose from.

"The results of Kepler revealed that there are so many surprises," says Dr Kate Isaak, project scientist of the European Space Agency's CHEOPS (CHaracterising ExOPlanet Satellite) mission, launched in December 2019. "In our Solar System we have smaller, rocky planets closer in, and

large planets like Jupiter are further out. But other systems reveal hot Jupiters – huge gas giants that have orbits shorter than a few days around their host star. The geometry of the planet systems we are finding is very different from our own, and this is very exciting."

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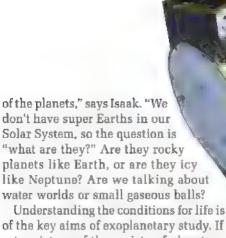
SEARCHING FOR 'SUPER EARTHS'

The key aim of CHEOPS is to carry out follow-up observations of bright stars already known to host exoplanets, especially those referred to as 'super Earths' and 'super Neptunes' - exoplanets more massive than their namesakes, yet smaller than gas giants like Jupiter and Saturn.

CHEOPS will measure the regular dip in the brightness of a star as an exoplanet passes in front - known as a 'transit' - enabling scientists to decipher that planet's size, among other properties. Ground-based telescopes will then measure the exoplanet's mass by observing how its gravitational pull causes the host star to 'wobble', which, combined with CHEOPS's transit data will enable astronomers to calculate the planet's 'bulk density'.

"Once we get the bulk density we can then start to work out the structure and composition





Understanding the conditions for life is one of the key aims of exoplanetary study. If we can get a picture of the variety of planets out there in the Universe, we can discover how common rocky planets like Earth are, whether these distant worlds have atmospheres, and whether they orbit in the 'habitable zone', in other words close enough to their star that liquid water can pool on their surface - a key condition for the survival of life as we know it.

[WST and CHEOPS will provide unprecedented studies of exoplanets, but they have to know where to look. This is where NASA's Transiting Exoplanet Survey Satellite (TESS) comes in. TESS was launched in April 2018 and has already begun its mission to monitor over 200,000 stars. It is expected to find over 1,500 potential exoplanet candidates, about 500 of which may be Earthsized and super Earths.

ARE WE ALONE?

Since our planet is the only cosmic body we know of that harbours life, it makes sense to seek out other rocky. Earth-like worlds in the hope of discovering whether life exists elsewhere in the Universe. One space probe that will be doing just that is PLATO, an ESA mission due to launch in 2026 that will look for small, rocky and icy bodies in the habitable zone around Sun-like stars. This, it is hoped, will enable astronomers to decipher just how common Earth-like planets are, and where to point future missions.

LIFE FINDS A WAY

The extreme conditions on many exoplanets may make them appear uninhabitable, but hardy organisms - known as extremophiles - have shown that life can survive in even the most hostile places.

Cyanidium caldarium is a type of algae known to thrive in hot, acidic conditions. This suggests that life might be able to survive on a planet like Venus, known for its scorching, acidic atmosphere. Meanwhile, Chroococcidiopsis is a bacterium found in hot, arid and super salty conditions, Crucially, It can survive radiation, meaning life could potentially survive on planets unshielded from the radiation of their host stars. Microbes have even been found beneath glaciers in Antarctica - cut off from light and oxygen, Could similar organisms be trapped beneath the polarice caps of Mars?

Perhaps most famous of all extremophiles is the tardigrade. These microscopic creatures have tolerated the extreme radiation and vacuum of space under controlled experiments by ESA. They can survive in temperatures from -272 °C to 150°C, and can live without water for years. What's more, if conditions become too extreme even for them, tardigrades can suspend all but their own vital functions and continue surviving in a form of suspended animation.

Extremophiles show just how robust life can be, and hint at the fact that they may be found even in the most unforgiving corners of the cosmos.

planets, all of them in our own Solar System," says Rigby. "We've since dropped one (Pluto), but learned about a thousand more, and one of the largest surprises is how different many of those systems are. The big question is: how did we get here? How did Earth form? How did the Sun form? How did the conditions for life, with lots of iron and nitrogen - not to mention water - on a rocky world, come to be?"

As Wolzsczan and Frail's discovery shows, you never know when the next breakthrough will be made, and curiosity is our best tool for seeking out these astronomical epiphanies. SF

by IAIN TODD lain is staff writer at BBC Sky At Night magazine

CHEOPS will help us

of and how they form

understand what exoplanets are made





NEW SECRETS OF THE SUPERNASSIVE BLACK HOLE

IN APRIL 2019, SCIENTISTS UNVEILED
A PHOTOGRAPH OF A COSMIC PHENOMENON
THAT DEFIES THE LAWS OF PHYSICS, MAKING
HEADLINES WORLDWIDE. SO HOW DID THEY
DO IT, AND WHAT DOES THIS LANDMARK
ACHIEVEMENT ACTUALLY TEACH US?

MARCI SCHOWN



ednesday 10 April 2019 was an epochmaking moment in the history of science. At six simultaneous press conferences worldwide, an international team of astronomers unveiled the first ever image of a black hole. "It was one of the most exciting days of my life," says Feryal Özel of the University of Arizona in Tucson, who heads the modelling team. "For me, it's the culmination of nearly two decades of work."

In fact, the team observed two black holes: Sagittarius A*, a supermassive black hole in our own Milky Way weighing 4.3 million times the mass of the Sun, and a cousin in the galaxy M87, which is about 1,000 times bigger. The first image revealed is of the supermassive black hole at the heart of M87. Sagittarius A*, because it's smaller, was circled by matter many times while being observed, yielding a blurrier picture.

The image of the black hole in M87, since named Powehi, shows detail smaller than the extent of its event horizon, the point of no return for in-falling light and matter. It is only possible to see such exquisite detail because the intense gravity of each black hole acts like a lens, which makes the image appear five times larger than its horizon.

The horizon in M87 shows up as a dark shadow backlit by intense radio waves, emitted by matter heated to incandescence as it swirls down through an accretion disk (gas and dust that is orbiting the object) onto the black hole. The halo around it is brighter on one side than on the other. "This is because the accretion disk is spinning, causing

the light from the part coming towards us to be boosted relative to that from the part that's receding," says Ozel.

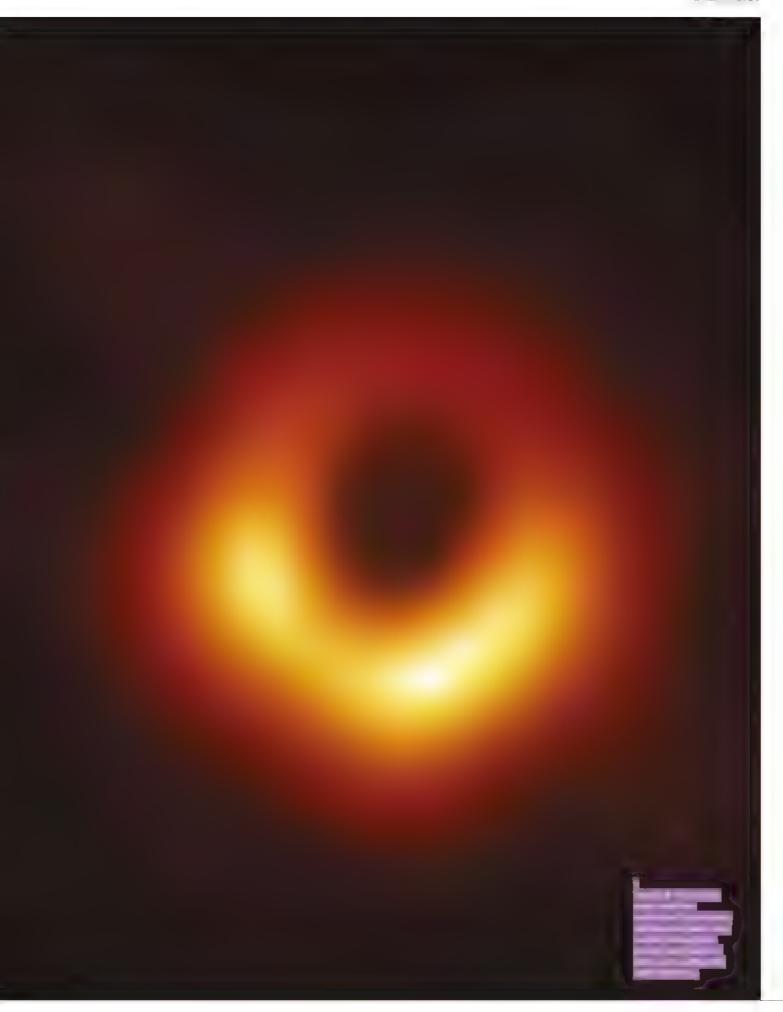
The remarkable M87 image was obtained by the Event Horizon Telescope (EHT), an array of radio dishes scattered around the globe which have been harnessed together to simulate a giant telescope the size of the Earth. Having an Earth-sized telescope is the key to imaging a target as tiny as a black hole, because the resolution of such a telescope—the fineness of the detail it can discern—depends on the maximum separation of its component parts.

STELLAR OR SUPERMASSIVE?

A black hole forms when matter is compressed into a volume so small that its gravity becomes too intense for anything, even light, to escape. This makes a stellar-mass black hole anywhere in our Galaxy too small for us to see with any Earthbound telescope. But nature has seen fit to create a second population of black holes. These are 'supermassive' ones with masses of up to 50 billion times the mass of the Sun, one of which lurks in the heart of almost every galaxy. However, on account of being very far away, these behemoths are as difficult to image as stellar-mass black holes in our own neighbourhood. Except in two cases: Sagittarius A*, which is just 27,000 light-years away, and its more massive seven-billion-solar-mass cousin in M87, at a distance of 56 million light years. "This is why they were chosen as targets for the EHT," says Özel.

There is also the matter of where to look in the light spectrum. High-energy electrons spiralling in the intense magnetic fields extending from a black hole's accretion disk generate radio waves, which have the advantage that they can easily penetrate the dust shrouding the centres of galaxies and so reach the Earth. Özel is an •

"THE EVENT HORIZON TELESCOPE (EHT) IS AN ARRAY OF RADIO DISHES HARNESSED TOGETHER TO SIMULATE A GIANT TELESCOPE THE SIZE OF THE EARTH"



We do, however, have a reasonable understanding of how stellar black holes form

DYING STAIL

Once stars run out of fuel, they die in one of two ways. Smaller, Sun-like stars splutter out of existence and form red giants and white dwarfs, while stars 10 or more times larger go supernova before becoming a black hole.



SOPERADRA

With the fuel spent, the outward pressure of the nuclear reaction can no longer resist the star's own gravity. The remaining material collapses in on itself and impludes in a supernova, spitting material into space.



TOLLAPSE

After this violent explosion, gravity pulls the remaining material together. These gravitational forces crush what's left into a singularity a single point of almost zero volume but infinite mass, and hence infinite density.



RLACK HALF

All that mass squeezed into an infinitely small point means that the singularity's gravity becomes so strong that nothing not even light can escape its pull, giving rise to what we know as a black hole.



BHOW

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• expert in simulating what the turbulent environment of a black hole surrounded by a super-heated accretion disk should look like at different wavelengths. "It turns out that the optimum wavelength is 1.3mm," says Özel. "Not only is it possible to see through the accretion disk to the hole,

but our Galaxy and the Earth's atmosphere are transparent to radio waves at this wavelength." Despite this wavelength being used, though, water vapour in the atmosphere can still absorb some of the precious radio waves. For this reason, the EHT's astronomers chose a time of the year to make the observations that maximised the dryness at all telescopes, which are located in places as far-flung as Chile, Hawaii and Greenland. "The optimum time is from the

end of March till the end of April," says Ozel.

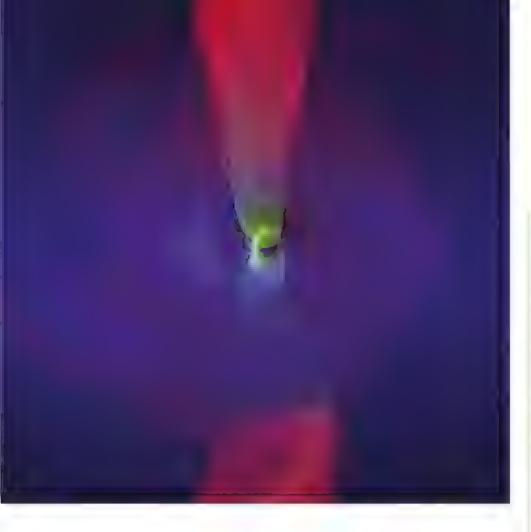
In April 2017, the EHT observed with telescopes at eight sites; in 2018, a dish in Greenland was added, upping the total to nine. Now, with the addition of a radio dish at Kitt Peak National Observatory in Arizona, there are 10, but it's the observations made in 2017 that have yielded the images of Sagittarius A* and M87.

In each observing run, data from each site is recorded on hard drives. Ordinary drives malfunctioned in the low pressure at the high-altitude telescope sites, and had to be replaced by special ones developed for the space programme. In 2017, a total of 960 drives, each with a capacity of six or seven terabytes — capable of storing 1-2 billion photos — recorded a whopping five petabytes of data. The disks, which together weighed more than half a tonne, were flown to Massachusetts and Bonn in Germany, where the signals from each site were combined on purposebuilt supercomputers known as 'correlators'.

The individual dishes of the EHT can be considered as tiny elements of a filled-in dish the size of the Earth. But whereas the radio waves impinging on each element of a filled-in dish



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are reflected to a focus where they are naturally combined, this does not happen for the 'elements' of the EHT. The process must be mimicked by playing back the signals on a computer and exactly reproducing the time delays there would naturally have been between them at the focal point.

Getting the signals perfectly synchronised is only possible because at each dish they are recorded alongside clock signals from a super-stable atomic clock. But combining the signals is still hugely time-consuming, because you need to compensate for delays caused by things such as different atmospheric conditions. This is why it took so long to analyse the data.

Even this tremendous feat of computing is still only half the job, though. Once that's been done, it's still necessary to determine what distribution of matter actually caused the pattern of radio waves observed. "Understanding what's going on requires figuring out what's happening over a huge range of scales," says Ozel.

PREDICTIONS PROVED ACCURATE

What's remarkable is that physicists like Özel were so successful, and that the image of the black hole in M87 was so close to what they expected to see. But, although this was cause for celebration among physicists, it left many laypeople underwhelmed, thinking that they had seen it all before. "We are victims of our own success!" admits Özel. "Artist's impressions and movie simulations of black holes, based on physicists' predictions, have turned out to be correct. But those holes were pretend ones. The difference now is that we are seeing the real thing."

Özel says she's "ecstatic" at being part of the team that obtained the first image of a black hole, but that it's also a huge relief. "Our predictions could have been completely off," she says. "Thankfully, we got the physics right!"

Among other things, the image of the nucleus of M87 has yielded the mass of its black hole. The diameter of a hole's event horizon goes up by 6km for each solar mass. Consequently, by measuring the width of the hole in the image and knowing the distance to M87, it has been possible to determine that it weighs in at 6.5 billion times the mass of the Sun. "This chimes perfectly with the mass deduced from how fast the hole's gravity is whirling round nearby stars," says Özel. "That puts it in the top 10 per cent of black holes by mass."

Perhaps the most remarkable thing about the image, however, is the sharp 'photon ring' that marks the inner edge of the doughnut of light around the hole. This is the point at which light plunges across the event horizon, never to be seen in our Universe again. EHT team member Heino Falcke of Radboud University in Nijmegen, the Netherlands, puts it in perspective: "We have seen the gates of Hell at the end of space and time."

"The hole is a part of our Universe permanently screened from view," explains Özel. "A place where our current physics cannot reach."

Our best current description of black holes is Einstein's theory of gravity.

"WE HAVE SEEN THE GATES OF HELL AT THE END OF SPACE AND TIME"



"STEPHEN HAWKING SUGGESTED THAT GENERAL RELATIVITY MAY BREAK DOWN AT THE HORIZON OF A BLACK HOLE"

• However, the General Theory of Relativity is likely to be an approximation of a deeper theory, since it breaks down at the centre of a black hole, where it predicts the existence of a nonsensical point of infinite density. Such a 'singularity' is screened from view by the horizon. The late Stephen Hawking suggested that General Relativity may also break down at the horizon of a black hole, and that the horizon might not actually be the surface of no return everyone believes it to be.

"We have not seen a departure from Einstein's theory yet," says Özel, "but finding such a discrepancy would be hugely important." Life increases the second of t

Einstein, who never actually believed that black holes could exist in reality, would have both been pleased that his theory has survived, and astonished that such a nightmarish prediction of this theory turns out to be real.

"The fact that Einstein's theory, formulated in 1915, so accurately predicts what we have seen in such an extreme environment, is a triumph for science," says Özel. "Until now, the horizon of a black hole was no more than a mathematical formula on piece of paper," she says. "Now it is a real thing in the real Universe."

LOOKING TO THE FUTURE

The long-term plan with the EHT is to observe Sagittarius A* and Powehi over many years, to see how they evolve as they swallow gas and rip apart stars. The hope is that we will get to understand things such as how they launch their jets. It is via these channels of super-fast matter — often accelerated to close to the speed of light — that supermassive black holes, despite their relatively tiny size, control the stellar content of their parent galaxies.

"We want to know whether the jets are launched at the horizon and how they are focused and collimated," says Özel.

In the 1990s, astronomers using NASA's Hubble Space Telescope in Earth orbit discovered that there is a supermassive black hole lurking in the heart of pretty much every galaxy. Why this is the case remains one of the great unsolved mysteries of cosmology, and it's one that's unlikely to be solved by the EHT. Other mysteries also persist. How quickly after the Big Bang were supermassive black holes born? Did they form in the hearts of newborn galaxies, or were they actually the seeds around which galaxies formed? Watch this space!

In the meantime, the first ever image of a black hole may look fuzzy, but sharper images will be obtained in the years to come. Very probably, it will go on to become one of the most iconic images in the history of science, alongside other famous pictures such as the Apollo 8 image of Earth rising above the Moon, or our first glimpse of the double spiral staircase of DNA.

"We humans should be proud of ourselves," says Özel. "It's easy to be overwhelmed by everyday events on Earth, but we should take some time to think, 'We have done this amazing thing. We have seen to the edge of space and time'."

ANATOMY OF A BLACK HOLE

. ACCRETION DISK

The part of the black hole that gives away its location. Here, stars, gas and any other material nearby spiral towards the hole at blistering speeds, producing enormous amounts of electromagnetic radiation that we can detect here on Earth. The objects sucked into the black hole become more frantic and crowded as they near the event horizon. Some are dragged beyond this point into the hole itself, while others are blasted outwards to create a jet.

2. RELATIVISTIC JETS

Pop culture suggests that nothing scapes a black hole, but that's not quite true. Astronomers have observed jets of particles streaming out of black holes so long and flerce that they break out from their galaxy. To borrow an analogy from Konstantinos Gourgouliatos, a theoretical physicist at the University of Durham, this is like water coming out of a tem-wide hose pipe and travelling 80 per cent of the way across the Earth (that's 10,000km).

Our best models suggest that black holes twist the fabric of space-time at their poles. This effect coils magnetic fields, creating a cosmic corkscrew that accelerates particles close to the speed of light before firing them out into the void. At the same time, a magnetic dual-carriageway forms at the black hole's equator—this causes the magnetic field lines to twist and tangle, producing another particle accelerator effect.

These two effects create the fastest particles in the Universe, knocking at the door of the cosmic speed limit: the speed of light. In the long term, data from the EHT should help us understand this comic, marvel in better detail.

3. PHOTON SPHERE

As material nears the event horizon, it emits photons (light particles). Normally these would travel outwards in straight lines, but at the cusp of the black hole its gravity bends the photon's path so that we observe a bright ring surrounding a spherical 'shadow'. The EHT will hopefully, in time, reveal more about both.

4. INNERMOST STABLE ORBIT

The imperedge of the accretion disk. This is the final region that material orbits before tumbling past the point of no return.

5. EVENT HORIZON

This is where the black part of the black hole begins. Beyond this point material cannot escape the black hole's grip. More accurately, the escape velocity needed to free itself from the hole's gravitational pull is greater than the speed of light.

B. SINGULARITY

All the matter and energy sucked into the black hole ends up here, at its centre: huge amounts of matter and energy are crushed into in an infinitely small space, giving rise to the black hole's gravitational pull. World-renowned theoretical physicist (and science consultant on the film interstellor) Kip Thorne has described a singularity as "a location where the laws of physics break down."



HOW WE KNOW BLACK HOLES EXIST...

WHY HAVE PHYSICISTS BELIEVED FOR SO LONG IN OBJECTS THAT UNTIL NOW HAD NEVER BEEN SEEN?

Karl Schwarzschild was a professor of astronomy at Berlin Observatory who, on the outbreak of WWI, volunteered for the German army. He did not have to: he had a good job and was 40 years old. But he was Jewish, anti-Semitism was on the rise in Germany, and he wanted to prove that he was just as German as everyone else.

Schwarzschild ran a weather station in Belgium, calculated shell trajectories with an artillery battery in France and, at the end of 1915, found himself on the Eastern Front. There, he developed blisters in his mouth. They spread over the whole of his body and he was sent to a field hospital, where he was diagnosed with *Pemphigas vulgaris*, a rare autoimmune disease in which the immune system attacks the skin.

Schwarzschild knew it was serious because the skin is the largest organ. It is through the skin that heat is lost and so, when it is compromised, it is not possible to control body temperature. Also, the skin is a barrier against microorganisms and so, when that barrier is breached, a person is prone to life-threatening infection. The condition remains incurable today, although it can be treated with steroids. But in 1915 there was nothing.

To distract himself, Schwarzschild turned to physics. Back in Berlin, he had been aware that Albert Einstein was working on a revolutionary new theory of gravity. And when he learned that Einstein had presented it in four



"EINSTEIN WAS
ANNAZED TO
RECEIVE A LETTER
FROM THE EASTERN
FRONT, AND EVEN
MORE AMAZED TO
FIND A SOLUTION
TO HIS EQUATIONS"

lectures in November 1915, he obtained and devoured a written summary.

FROM NEWTON TO EINSTEIN

Isaac Newton imagined that there was a force of gravity between the Sun and Earth, like an invisible tether that kept Earth trapped in orbit. Einstein realised this was incorrect. In fact, a massive body like the Sun creates a valley in the space-time around it, and Earth travels around the upper slopes of the valley like a roulette ball in a roulette wheel.

Einstein had replaced Newton's one equation describing gravity by 10. So working out how space-time is warped by a given mass was very difficult. But, incredibly, Schwarzschild found a formula for the valley-like space-time curvature caused by a spherical mass like a star. He sent it to Berlin. Einstein was amazed to receive a letter from the Eastern Front, and even more amazed to find a solution to his equations, which he had considered impossible. The following week he presented the results at the Prussian Academy.

But Schwarzschild had not finished.



MONSTROUS ENTITY

Lying in his hospital bed, Schwarzschild further realised that, if the mass of a star was squeezed into a smaller and smaller volume, the valley of spacetime around it would become steeper and steeper until eventually it would become a bottomless pit out of which nothing, not even light, could escape. Today, everyone in the world knows the name of what Schwarzschild had discovered but the term 'black hole' would not be coined for another half century. He again sent his solution to Einstein, who presented it in Berlin, although he did not believe nature would ever implement such a monstrous entity.

In the spring of 1916, Schwarzschild was moved to a hospital in Berlin, where he died. He was just 42.

The main problem in astronomy is

that the Universe is big. There are two trillion galaxies, each with about 100 billion stars. Finding an interesting one is harder than finding an interesting sand grain among all the sand grains on Earth's beaches. What sign might reveal that a star was unusual?

Fast forward to 1971 Herstmonceux Castle, the Sussex home of the Royal Greenwich Observatory. Paul Murdin was an astronomy researcher with a young family to support, and was in need of a permanent job. He had to make a name for himself, and he had an inkling of how to do it: by studying X-ray sources. Such highenergy light would be emitted by matter heated to millions of degrees. The previous year, NASA had launched Uhuru,

the first satellite to survey the sky for X-ray sources, and Murdin obtained the catalogue.

He noticed there was a bright X-ray source, christened Cygnus X-1, in the constellation of Cygnus. The only unusual star in the field was a blue supergiant called HDE 226868, many times the mass of the Sun and pumping out hundreds of thousands of times more light. The star could not be the source of the X-rays – but maybe it was orbiting something that was.

Murdin's colleague Louise Webster was measuring the speeds of stars, so he asked her to measure the speed of the blue supergiant. And, sure enough, she found it was orbiting an invisible companion, once every 5.6 days. From the speed that the supergiant was being whirled around, this companion had to have a mass of at least four, and probably six times the mass of the Sun. The only compact stars that were known - white dwarfs and neutron stars, the latter discovered by Jocelyn Bell Burnell only four years earlier - were not massive enough. Only one candidate remained: a black hole.

THEORY BECOMES REALITY

Incredibly, the monstrous, nightmare entity predicted by a man dying in a bed in a field hospital on the Eastern Front half a century earlier, actually existed in the real world! It was matter ripped from the blue supergiant and heated to incandescence as it was sucked down onto the black hole that was generating the X-rays. Murdin and Webster wrote a joint paper in the journal Nature. Murdin got his full-time job and a new house, and became the first person in history ever to have his mortgage paid by a black hole. SF

IN MARCUS CHOWN

Marcus is the author of Infinity In The Palm of Your Hand: Fifty Wonders That Revea An Extraord nary Universe (Michael O'Mara Books, 2018)





The deeper
we look into the
vastness of space, the
further back in time we are able
to see. Now, NASA's RELICS project
is pushing this phenomenon as far
as it can in an attempt to observe
galaxies that formed at the
very beginning of the
Universe

s the fireball of the Big Bang expanded and cooled, it went from white-hot to cherry-red before finally fading into invisibility. The Universe was plunged into blackness and the resulting cosmic dark age stretched on interminably. Over time, the Universe doubled in size, doubled once more, over and over again, then, one day, something extraordinary happened. The dark age came to an end. Across the entire length and breadth of the Universe, stars began switch on like lights on a

Christmas tree.

The first stars either came together under gravity to create the first galaxies, or were actually born in the clouds of gas and dust that made up the first galaxies. And the hunt to find these first galaxies is hotting up. One project – the Re-ionization Lensing Cluster Survey (RELICS) – has found around 300 galaxies that existed in the first billion years of the Universe's history. One galaxy in particular is so old that the Universe it occupied was a mere 3 per cent of its present age of 13.82 billion years. Such objects appear in astronomers' telescopes like persistent after-images, their light

having travelled across space for billions upon billions of years before reaching us.

BACK IN TIME

More than 40 astronomers in many countries have been involved in the RELICS project, contributing hundreds of hours of observing time on the Hubble Space Telescope and the Spitzer Space Telescope. However, the principal observing instrument is the Universe itself. The gravitational fields of the massive clusters of galaxies that pepper the Universe act like giant lenses that focus and magnify the light of more distant galaxies that are often far too faint to see by any other means. "We take advantage of nature's own telescope," says Dan Coe, principal investigator of RELICS at the Space Telescope Science Institute in Baltimore.

To find the useful lensing clusters that would help him spot the oldest galaxies, Coe searched through Hubble's archive of images and a recent catalogue of around 1,000 galaxy clusters observed by the European Space Agency's (ESA's) Planck satellite. Planck's principal purpose was to image



• the cosmic background radiation the 'afterglow' of the Big Bang fireball itself — but the 'far-infrared' light it picked up also comes from warm dust in galaxy clusters. "We ended up with 41 massive galaxy clusters," says Coe "We selected them for their extreme mass, which makes them enormously powerful gravitational lenses."

In the immediate neighbourhood of each cluster are literally thousands of ghostly images of distant galaxies that by chance have been 'gravitationally lensed' by the cluster. But most are of galaxies that are not at great distances, and so not in the very early Universe. "The trick to finding truly ancient objects is to look for lensed galaxies that appear in infrared images from Hubble and Spitzer images, but not in Hubble images taken at visible wavelengths," says Coe. But to understand why this reveals ultra-distant, ultra-early galaxies, we need to look at the concept of 'redshift'.

SEEING RED

When the Universe was younger, it was smaller. The most distant galaxy in RELICS existed more than 13 billion years ago when the Universe was less than one-thousandth of its current size. As space expanded over that time, it also stretched the light from that galaxy. Since red light has a longer wavelength than blue light, the light of such galaxies is shifted to the red end of the spectrum, or 'redshifted'.

The light of the earliest galaxies has been so severely redshifted that its visible light now appears as 'infrared', at wavelengths beyond the red end of the spectrum. Thus, the galaxies have the unique characteristic of being invisible to Hubble's Advanced Camera for Surveys but visible to Hubble's Wide Field Camera 3, which is sensitive to infrared light. Spitzer's infrared imaging instruments are also important in determining whether galaxies are at extremely high redshift, or less distant and merely intrinsically red due to dust or old age.

The gravitational lens formed by a galaxy cluster zooms in on a tiny region of the night sky so it might be expected that such a region would be more likely to contain empty space than any galaxies in the distant Universe. However, it turns out that galaxies in the early Universe were much smaller and a lot more numerous, so actually there is a good chance of them appearing in the field of view of any given gravitational lens. This explains why RELICS has found not a handful of galaxies, but around 300. These date back to the first billion years of the Universe and include

"THE MOST DISTANT
GALAXY IN RELICS
EXISTED OVER 13
BILLION YEARS AGO"



the brightest ones ever observed from that epoch.

Among the 300 galaxies is the rather unimaginatively named SPT0615-JD. It has a redshift of 10, which means it existed when the observable Universe was less than one-tenth of its current diameter and only about 400 million years old (the current record-holding galaxy, found in a previous survey, actually has a redshift of 11). The lensing effect has distorted the galaxy into an extended 'arc' and Coe says further observations will be needed to discern any details. Nevertheless, it is already obvious that SPT0615-JD is quite unlike

BFI.OW
Oval sky map of the cosmic microwave backg ound (CMB) as seen by the Planck satellite. The CMB is radiation eft over from shortly after the Big Bang The differences due to density variations after the Big Bang Denser regions attracted more matter eading to the

formation of galaxies

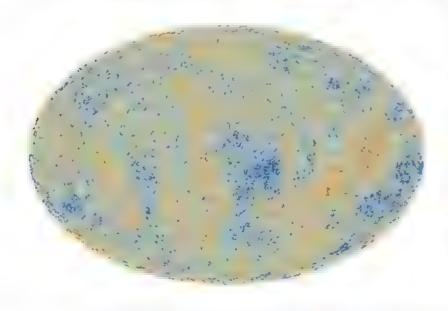
a present-day galaxy. It is only one-twentieth of the diameter of the Milky Way, has less than one-hundredth of its mass, and none of its regularity. In fact, Coe and his colleagues refer to it as a 'smudge'. The other 300-odd galaxies are similarly small.

If we had a time machine and could go back to a redshift of 10. we would find ourselves in a different Universe. There would be no galaxies with distinct structures like today's 'giant ellipticals' and 'spirals'. In their place we would see tiny, disordered blobs, often less than one-hundredth the diameter of the Milky Way. Such galaxies would be undergoing star formation at a ferocious rate, often hundreds or thousands of times faster than galaxies in today's Universe. There are at least two reasons for this. First, gas – the raw material of stars – was plentiful. Second, galaxies at a redshift of 10 were thousands of times

more numerous than today's galaxies and far closer together, resulting in frequent collisions and mergers, which triggered intense bouts of star formation.

The fact that mergers were such a dominant feature of the early Universe may tell us something important about the galaxies of that time. "Very possibly, we are seeing the building blocks of today's galaxies," says Coe. "As time passed, these ancient galaxies were destined to collide and merge over and over again. In fact, our Milky Way could well have undergone thousands of such mergers to reach its current size."

According to Coe, we have not yet seen the first galaxies, since even the earliest galaxies we've found contain older, bright red stars that are near the end of their lives. The first galaxies could conceivably have formed a mere 200 million years after the Big Bang. The best hope of finding them, says Coe, is by using the James •





RELOW Supermass ve black holes, like the one in this

illustration, may have played a key role in transforming the nature of gas in the early Universe

 Webb Space Telescope, the successor of Hubble, which is due for launch in 2021. With its 6.5-metre primary mirror, it will orbit around the Sun at the so-called Lagrange-2 point, about a million kilometres from the Earth. Lagrange points are areas in space where gravity from the Sun and Earth balance out the orbital motion of a satellite.

Placing a spacecraft at any of these points allows it to stay in a fixed position relative to the Earth and Sun with a minimal amount of energy needed to change its direction.

DIGGING DEEPER

As James Webb will be sensitive to far-infrared light, it will be capable of detecting galaxies at ultra-high redshift. The hope is that the James Webb will shed light on 'cosmic re-ionisation', a key event which fundamentally changed

the nature of the gas floating throughout space in the early Universe. About 380,000 years after the Big Bang, the fireball had cooled sufficiently for electrons to combine with hydrogen and helium nuclei to form the Universe's first atoms. However, there is a mystery. Today, when astronomers observe the hydrogen gas floating in space, they discover that its electrons have been blasted away it has been 're-ionised'. The only thing that could have re-ionised the Universe is high-energy ultraviolet light. So where did it come from?

Planck observations indicate that re-ionisation began at a redshift of about 9. One possibility is that the responsible ultraviolet light came from the first stars, which may have started forming just 100 million years after the birth of the Universe. Another possibility is that the ultraviolet light came from matter heated to incandescence as it swirled down onto supermassive black holes. These formed in the hearts of newborn galaxies, causing them to shine as super-bright quasars. Coe thinks it's possible that multiple sources re-ionised the Universe. "Maybe stars are responsible for most of the re-ionisation and quasars for some,"





RIGHT
Engineers assemble the primary mirror of the James Webb Space Telescope due for aunch in 2021

he says. "And it is even conceivable that there might be another source — perhaps the annihilation of particles of dark matter, mysterious invisible stuff known to outweigh the stars and galaxies by a factor of six."

But the hope is that James Webb will help answer many more questions. Like when did the first stars form? Such Population III stars, as they are known, would have contained only hydrogen and helium from the Big Bang but no heavier elements such as oxygen, calcium and iron, which can be made only by nuclear reactions inside stars. Nobody has yet spotted any Population III stars, which are expected to have been much more massive than today's stars and raced through their lives at breakneck speed in only a few million years before detonating as supernovae.

Hubble has already spotted galaxies making the transition from amorphous blobs to ordered structures, rotating like the great spiral of the Milky Way, but James Webb may find the earliest galaxies that exhibited such ordered rotation. In fact, there is a possibility that Coe and his team may be able to determine this with follow-up observations using the Atacama Large Millimeter/submillimeter Array. If they can detect emission from oxygen in any of their ancient galaxies, differences in the frequency of that emission across the galaxies could reveal whether some parts are moving towards us and some away in a systematic way. Such a doppler effect is the smoking gun for galaxy rotation.

James Webb may settle other questions, such as when did the first galaxies form? What did they look like? Are they truly the building blocks of galaxies like the Milky Way? "We have observed galaxy evolution over 13.4 billion years of cosmic time — that's 97 per cent of the way back to the beginning," says Coe. "I am most excited to see the missing 3 per cent — the last remaining jigsaw piece." SF

"THE JAMES WEBB TELESCOPE MAY ALSO SETTLE OTHER QUESTIONS, SUCH AS WHEN DID THE FIRST GALAXIES FORM?"



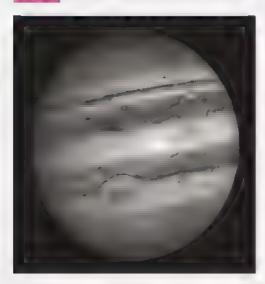
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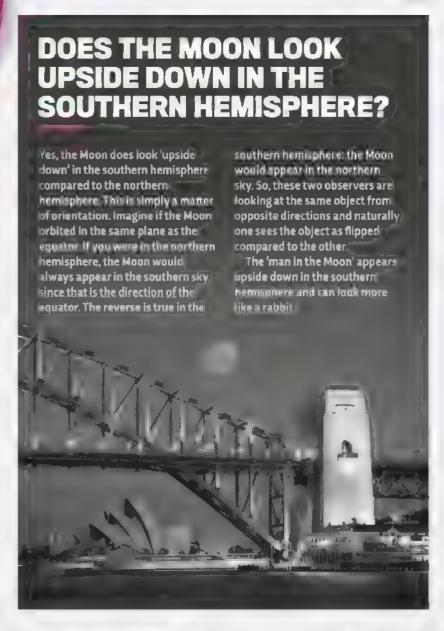


Astronomers have found that the magnetic field strengths near supermassive black holes can be as strong as their intense gravitational fields. These magnetic fields can expel material from around the black hole to form highly energetic outflows called 'jets'. However, this process is not acting on material that has already passed beyond the black hole's event horizon (where gravity is so strong not even light can escape). Such material would need to be accelerated to at least the speed of light to escape, and Einstein's Ceneral Relativity shows this would require an infinite amount of energy. No magnet, however powerful, could provide this

HOW WOULD OUR SOLAR SYSTEM BE DIFFERENT IF JUPITER HAD BEEN BIG ENOUGH TO BE A STAR?

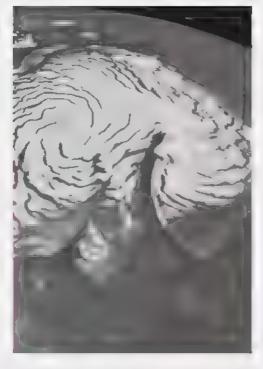


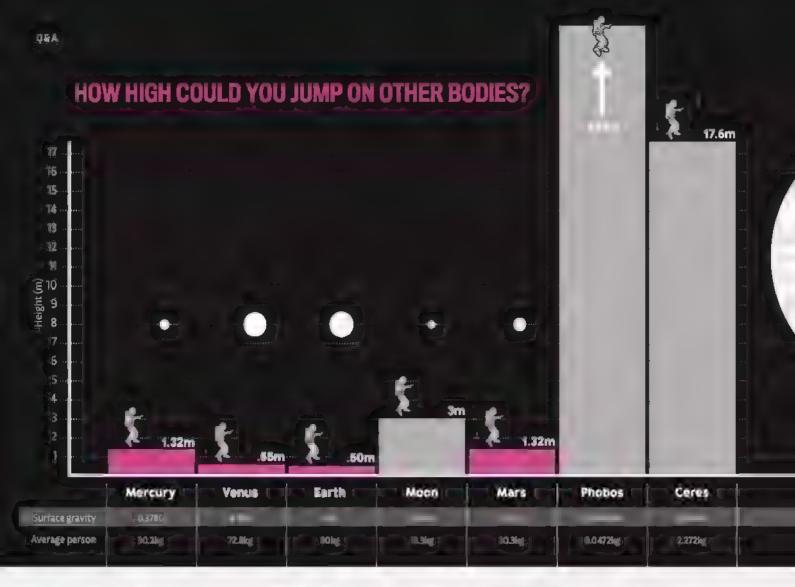
If Jup ter had carried on growing, it would eventually have become a star lifthis star was a barely luminous 'brown dwarf', it would have only a minor effect on planetary orbits. But if it had become a more massive star, it would probably have prevented planets from forming in stable orbits. In any case, it would have greatly increased the amount of radiation their surfaces receive, so the development of life in our Solar System would have been far less likely.



WHAT DOES MARTIAN WATER TASTE LIKE?

Most of Mars's water isn't present as aguid it sice, mixed in with the soil Mars has such low atmospheric pressure that pure water ce sublimes directly from solid to gas without ever melting nto liquid. There is evidence that the Red Planet may occasional y have some iguid water but it would be undrinkably salty If you distilled the water inside your pressurised habitat though it would be quite safe. to drank

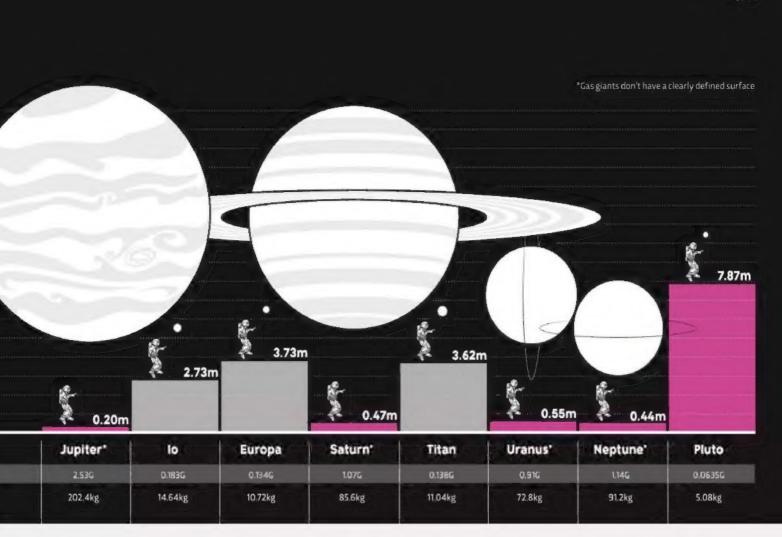






DOES THE SUN MAKE A SOUND?

The Sun generates sound in the form of pressure waves These are produced by huge pockets of hot gas that rise from deep within the Sun, travelling at hundreds of thousands of miles per hour to eventually break through the solar surface. As a result the Sun's atmosphere is seething like a pan of boiling water The characteristics of sound waves such as speed and ampitude, depend on the material they pass through and can be used to study the Sun's deep interior Unfortunately, the same ength of these waves is measured in hundreds of miles, so they're outside the range of human hearing





HOW FAR FROM EARTH COULD OUR RADIO SIGNALS BE DETECTED?

While commercial radio broadcasts began around 100 years ago, these early transmissions used frequencies that were either mopped up by the atmosphere or drowned out by radio emissions from the Sun. In contrast, military radar transmissions set up during the Cold War to detect incoming ballistic missiles have the power and frequency characteristics to be detected over hundreds of light-years - and have already broadcast our existence to any aliens within around 60 light-years of the Earth.

DOES EARTH HAVE A SECOND MOON?

There is only one permanent natural object that orbits the Earth: the Moon, Several small asteroids are 'quasi-satellites' of the Earth; from our perspective, they appear to follow a loop around our planet, but they are not actually orbiting us.

Occasionally, Earth captures an asteroid in a temporary orbit and these can be considered moons or 'minimoons'. One such object, the asteroid 2006 RH120, was a car-sized 'moon' of Earth that orbited from September 2006 to June 2007.





WHAT DOES SPACE SMELL LIKE?

We can't smell space directly, because our noses don't work in a vacuum. But astronauts aboard the ISS have reported a metallic aroma like welding fumes on their spacesuits following a spacewalk. The Rosetta spacecraft also detected compounds responsible for the smell of rotten eggs, bitter almonds and cat urine, boiling off the surface of comet 67P/Churyumov-Gerasimenko.

COULD WE EVER DETECT OTHER UNIVERSES?

The idea that the Universe is one of many, making up one. truly infinite 'multiverse' is among the most intriguing and controversial - theories in modern physics. It's based on attempts to find the one true 'Theory of Everything' (ToE) that describes all the particles and forces making up reality in a single set of equations. Some attempts to create the ToE suggest there are many

different universes, each with different laws of physics. These differences may reveal the existence of universes neighbouring our own, but exactly how they'll be revealed is unclear. One possibility is via distortions in residual heat from the Big Bang. This has been precisely mapped and may contain patterns consistent with the lurking presence of another universe.

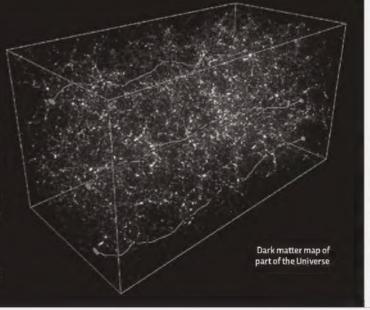


COULD THERE BE MATERIALS ON OTHER PLANETS THAT WE DON'T HAVE ON EARTH?

Yes, absolutely - because every so often, we get a delivery from meteorites. Chemical analysis has so far identified around 300 minerals from this deep space debris, including around 40 unique to these meteorites. One of the most intriguing materials was found in the Allende meteorite, which exploded over Mexico in 1969. After analysing the debris, scientists in 2012 announced the discovery of a material that not only has never been seen on Earth but wasn't even known to be possible. Named 'panguite' - after the giant Pan Gu who created the Earth in Chinese mythology - it consists of a bizarre mix of elements, including titanium, zirconium and scandium.

COULD DARK MATTER JUST BE DEAD STARS AND PLANETS FLOATING IN THE **DEPTHS OF SPACE?**

Some astronomers have indeed theorised that dark matter might just be ordinary matter that we cannot see, rather than an exotic, as-yet-undiscovered particle. This ordinary matter could include black holes, neutron stars, brown dwarfs, white dwarfs, faint red dwarfs and even solitary planets. These objects, collectively known as MACHOs (Massive Astrophysical Compact Halo Objects), emit very little light, but they can be detected if they pass in front of or near a background object (via the way that their gravity bends the light from the more distant object). However, studies to date have concluded that MACHOs can only account for a tiny fraction of the missing mass in the Universe. So the nature of dark matter remains a mystery.



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